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Electrification as an alternative for combustion technologies in existing Finnish district heating networks

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Abstract of master's thesis

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Abstract

The phase-out of fossil fuels leads to new production side investments in the Finnish district heating (DH) networks. A natural option to replace fossil fuel-based heat production would be either biomass heat only boilers (HOB) or combined heat and power production (CHP). However, sustainable domestic biomass resource sufficiency may limit the potential of biomass especially in coastal areas in Finland. The future price level of biomass is highly uncertain and depends on most of all the future competition of the resource in and outside the heating sector, as well as the location of the studied network.

As alternatives for biomass, heat pumps, electric boilers, and heat storage have been studied in this thesis. The power-to-heat technologies enable a wider sector coupling of electricity and heat sectors, where the heat sector with considerably larger inertia would provide valuable flexibility to the electricity sector with increasing amounts of intermittent renewable production. At the same time, the heat production would benefit by scheduling the production on the hours with low electricity prices. In a literature review, it was found that geothermal heat and ambient air would be the two heat sources that would be achievable anywhere in Finland and be unlimitedly available, and would thus be suitable for wider scale DH electrification.

By analyzing the cost-optimal configurations of the combustion-based technologies, heat pumps, electric boilers, and heat storage, it was found out that the optimal share of air-source heat pumps would be 40% of the total base load production, the remaining part constituting of biomass CHP. Electric boilers would provide a more cost-effective peak load alternative compared to wood pellet boilers due to their lower investment costs. The optimal storage size for the system would be 1% of the total yearly DH demand or more. Full electrification by air-source heat pumps and electric boilers would lead to an increase in heat production costs by 2.2EUR/MWh compared to the cost-optimal system.

Geo-source heat pumps were not found profitable according to the analysis. This was above all due to the high investment costs in the geothermal wells. Full electrification with geo-source heat pumps would lead to 11.7EUR/MWh higher heat production costs compared to the cost-optimal system. However, if the investment costs of the geothermal wells are to drop in the future, the geothermal heat would provide a more stable and technically more reliable heat source with a higher average coefficient of performance (COP) than ambient air. Nonetheless, the results of this thesis show that the air-source heat pumps would currently provide an interesting and scalable alternative for DH system electrification.

Keywords district heating, heat pumps, electrification, biomass resource sufficiency

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Tiivistelmä

Fossiilisista polttoaineista luopuminen johtaa uusiin investointeihin suomalaisessa kaukolämmöntuotannossa. Luonnollinen vaihtoehto korvaajaksi olisi lämmön erillistuotanto tai yhteistuotanto biomassalla. Biomassan potentiaalia saattaa kuitenkin merkittävästi rajoittaa sen resurssiriittävyys etenkin rannikkoalueilla. Biomassan hintatasoa tulevaisuudessa on vaikeaa arvioida, ja se riippuu muun muassa kilpailusta lämmityssektorilla ja sen ulkopuolella, sekä tarkasteltavan verkon sijainnista.

Tässä työssä lämpöpumppuja, sähkökattiloita ja lämpövarastoja on tutkittu vaihtoehtona biomassalle. Sähköön perustuvat tuotantomuodot mahdollistavat sähkö- ja lämmitysjärjestelmien yhtyeenkytkennän, jossa lämmitysjärjestelmä pystyy korkeamman inertiatason avulla tarjoamaan arvokasta joustoa sähköjärjestelmälle joka sisältää yhä enemmän vaihtelevaa uusiutuvaa tuotantoa. Samalla lämmitysjärjestelmä pääsee hyötymään yhteenkytkennästä ajoittamalla lämmöntuotantoa alhaisen sähkön hinnan tunneille. Kirjallisuuskatsauksessa todettiin, että geoterminen lämpö sekä ulkoilma tarjoavat lämmönlähteet jotka ovat saatavissa skaalatutuvasti kaikkialla Suomessa ja sopisivat siten laajempaan lämpöjärjestelmän sähköistämiseen.

Tarkastelemalla kustannustehokkaimpia lämmöntuotantoportfolioita sisältäen polttotekniikoita, lämpöpumppuja, sähkökattiloita ja lämpövarastoja kustannustehokkaimmaksi ilma-vesilämpöpumppujen määräksi osoittautui 40 % pohjakuormasta lopun pohjakuormakapasiteetin ollessa yhteistuotantoa biomassalla. Sähkökattilat osoittautuivat kustannustehokkaammaksi huippukuormakapasiteetiksi pellettikattiloihin verrattuna niiden alhaisten investointikustannusten vuoksi. Optimaalinen lämpövaraston koko järjestelmälle olisi tällöin 1 % tai yli verkon vuositason lämmönkulutuksesta. Järjestelemän sähköistäminen kokonaan ilma-vesilämpöpumpuilla ja sähkökattiloilla maksaisi 2,2 EUR/MWh enemmän kuin kustannustehokkain konfiguraatio.

Geo-lämpöpumput osoittautuivat työssä kannattamattomiksi. Tämä johtui ennen kaikkea korkeista investointikustannuksista reikien poraamiseen liittyen. Järjestelmän täysi sähköistäminen geo-lämpöpumpuilla maksaisi 11,7 EUR/MWh enemmän kuin kustannustehokkain konfiguraatio. Mikäli reikien poraamisen kustannukset kuitenkin laskevat tulevaisuudessa, tarjoaisi geoterminen lämpö paljon tasaisemman ja teknisesti luotettavan lämmönlähteen ulkoilmaa korkeammalla tehokertoimella. Kaikesta huolimatta työn tulokset osoittavat, että ilma-vesilämpöpumput tarjoavat nykyisellään mielenkiintoisen ja skaalautuvan vaihtoehdon kaukolämpöjärjestelmän sähköistämiseen.

Avainsanat kaukolämpö, lämpöpumput, sähköistyminen, biomassan resurssiriittävyys

Preface

This thesis was conducted for AFRY Management Consulting Energy practice team in Vantaa, to which I owe many thanks for the opportunity to write the thesis as well as to be involved in several interesting projects during my traineeship and hereafter. Especially I want to thank my thesis advisor Juha Känkänen for the guidance and insights around the topic. Secondly, I want to thank my colleague Jussi Närhi for providing the best possible peer support during the ups and downs of writing our theses. Many thanks are also in place for my thesis supervisor, Professor Sanna Syri, who gave clear and prompt guidance throughout the project.

Finally, I want to thank my friends and family who have reminded me of all the other things in life during the process. Especially, I am deeply grateful for my parents who have provided me all their support in every stage of my life.

Helsinki, 24th February 2020

Niklas Armila

Table of Contents

List of Abbreviations

ASHP	Air-source heat pump (in this thesis refers to industrial-scale air-to-water heat pumps)
Capex	Capital expenditure
CHP	Combined heat and power
CO_2	Carbon dioxide
COP	Coefficient of performance
DH	District heating
DHC	District heating and cooling
DSO	Distribution system operator
GSHP	Geo-source heat pump
GWh	Gigawatt hours
HOB	Heat only boiler
HP	Heat pump
kEUR	Thousand euros
kV	Kilovolts
LCOH	Levelized cost of heat
LHS	Latent heat storage
LHV	Lower heating value
LP	Linear programming
MEUR	Million euros
Mm^3	Million cubic meters
MW	Megawatts
MW_{fuel}	Megawatts fuel
MWh	Megawatt hours
MW_{th}	Megawatts thermal energy
NO_x	Nitrogen oxide
O&M	Operations and maintenance
Opex	Operating expenses
PV	Present value
SHS	Sensible heat storage
SO_2	Sulphur dioxide
TCES	Thermochemical energy storage
TES	Thermal energy storage
TWh	Terawatt hours
WACC	Weighted average cost of capital

List of Figures

List of Tables

1 Introduction

Due to climate change, the long-term goal of many countries is to become climate neutral or to achieve significant reductions in greenhouse gas emissions within a couple of decades. While energy production plays a major part in this context, the long-term policies usually also include discontinuing the use of fossil fuels for heat production over time.

The long-term strategy of the European Union is to become climate neutral by 2050. Already in its strategy for 2020, the EU had ambitious targets in reshaping the energy sector towards a more sustainable direction. (European Union, 2019). According to the EU strategy on heating and cooling, heating and cooling comprise half of the EU's energy usage. Approximately 75% of this is produced by fossil fuels. The Nordic countries are forerunners in bioenergy use. (European Commission, 2016).

As proposed by Juha Sipilä's former Government, Finland is to abandon coal in energy production by 2029 (Finlex, 2019). The current Programme of Sanna Marin's Government aims to a carbon-neutral Finland by 2035. The actions related to this goal include e.g. halving the usage of peat in energy production by 2030. According to the forecasts, the peat usage will cease during the 2030s as the carbon price increases. However, the Government intends to ensure the 2030 goal by adjusting the energy tax on peat if necessary in 2020. (Finnish Government, 2019).

After the coal ban and the gradual phase-out of peat, the major fossil fuels still in use in the Finnish district heating (DH) production would according to the current usage be natural gas, and to some extent also oil (Finnish Energy, 2019). The use of natural gas as a base load fuel is already relatively expensive due to high fuel prices, carbon price, and taxes. Expensive oil is already mostly used for peak load production. Increasing carbon price in the European Emission Trading System may also further incite to find replacements to fossil fuel based production.

Currently, a natural option to replace fossil fuels in DH seems to be biomass. The technology choice between combined heat and power production (CHP) and heat only boilers (HOB) depends among other factors on the electricity price and electricity price profile development. For example, an increasing amount of wind power in the system would favor new biomass HOB capacity investments instead of CHP (Dahl, et al., 2019).

However, the sufficiency of the domestic biomass feedstock supply to meet the demand that would originate from the transition from fossil fuels to biomass may be questioned. The supply of domestic wood-based biomass is highly dependent on the forest industry in Finland (The Finnish Climate Change Panel, 2015). With the current scenarios of increasing biomass use in energy production, it has been found that the domestic residuals from the forest industry may not be sufficient to fulfill the local demand for biomass in the future in the coastal areas in Finland (Pöyry Management Consulting, 2019). Furthermore, the residuals from the forest industry may also be utilized increasingly in other use cases, leading to more competition of the resource and increased prices. Promoting research on wood products with high added value and the sustainable exploitation of wood-based by-products is also one objective in the current Government Programme (Finnish Government, 2019).

In addition to the resource sufficiency, another perspective to the use of biomass is the short term emissions caused by combusting it. According to the computational methods combusting biomass is considered to have zero emissions. However, the period of this examination is several decades. Therefore, in the short term, biomass may even emit more CO_2 than its fossil fuel substitutes. (The Finnish Climate Change Panel, 2015). Logistics of biomass and the poor storage capabilities raise further problems for the increasing usage. (Pöyry Management Consulting, 2018).

An alternative way to develop the DH system would be to produce heat by electricity. This strategy is also supported by the European Union and the Finnish Government (European Commission, 2016); (Finnish Government, 2019). The strategy would couple the power and heat sectors, allowing the sectors to provide flexibility to one another. For example, heat could be produced by electricity when there is non-dispatchable excess production (such as wind power) available.

Together with heat storages and the thermal inertia of the DH network, this would provide both a competitive alternative for heat production to the DH system and valuable flexibility to facilitate the increasing amount of intermittent renewable-based power production. Besides the variable electricity prices, the competitiveness of this alternative would be based on heat pumps that utilize low-temperature heat from the environment as well as a smaller share of electricity. The heat from the environment may be considered renewable.

1.1 Research Objective

The research objective of this study is to find out the optimal share of heat pumps and the optimal size of heat storage in a typical medium-sized DH network in Finland. The research question could be formulated as:

> *"What would be the most economical amount of heat pumps and heat storages in an existing but reinvesting DH network?"*

The "existing" network refers to the dimensioning of the network for relatively high supply temperatures. Also, the investment costs of the network (pipes, pumps etc.) will hence not be considered. However, it is assumed that the production technologies would be replaced fully with new alternatives as they reach their end of life or are decommissioned due to a specific fuel ban, such as coal. A sensitivity analysis of the results in terms of biomass price will also be made.

The secondary goal of the thesis is to find out the cost difference between a fully electricity-based production portfolio alternative compared to the cost-optimal production configuration. The sensitivity analysis with the biomass price gives further insights in this and indicates a threshold after which a full electrification of heating would become profitable. The secondary research question could be formulated as:

“In which circumstances would a fully electricity-based production configuration be the most economically feasible alternative?”

The study is conducted for AFRY Management Consulting. The study aims to provide insights into the most economical pathways for future DH production investments in existing medium-sized networks. Especially, the potential of power-to-heat technologies when considering the new investments is examined.

1.2 Research Scope

As finding the cost-optimal production portfolio for a DH system is a highly multidimensional problem, several presumptions have been made. Instead of focusing on a very detailed optimization of the network control and possible locations for the studied plants, only an aggregate amount of capacities of different production technologies serving an aggregate heat demand is modeled. Typical fixed and variable costs for the technologies are gathered from the literature. Thus, the focus of the thesis is on the economical optimum, and not to find out the most optimal technical implementation for the system. This would not even be possible, as an artificial network that does not represent any specific real network is used. Instead, the network is an estimate of a typical Finnish middle-sized DH system, which enables us to achieve rough but more universally applicable results.

The studied production technologies include biomass HOB and backpressure CHP plants as conventional base load combustion technologies and centralized heat pumps as the alternative base load production technology. Thus, technologies such as solar thermal, nuclear HOB or CHP, and de-centralized heat pumps are excluded from the scope of this thesis, though they could also provide a non-combustion alternative for future DH production. Fossil fuels are excluded from the analysis also as peak load production, as they are assumed to retain only as reserve heat production in the future systems. Instead, wood pellets and electric boilers as peak load capacity are modeled.

Furthermore, the focus of the study is on a traditional DH system serving only a heat load. Thus, cooling networks are excluded from the thesis, though there would certainly be additional synergies between heating and cooling production if heat pumps are considered. Neither demand response in DH or bidirectional DH is studied, though they are mentioned in the literature part of the thesis.

1.3 Structure of the Thesis

The thesis consists of three sections: a literature review (chapters 2 and 3), empirical part (chapters 4 and 5) and discussion of the results and the findings (chapter 6). In chapter 2 the current state of district heating in Finland is overviewed and a demand profile for the modeled system is created. Chapter 3 includes some future aspects of district heating and reviews studies related to this. Chapter 4 discusses the model assumptions and the structure and objective of the modeling framework, as well as represents a more detailed description of the model used. Chapter 5 presents the results and the findings of the model runs. Finally, the conclusions of the thesis as a whole are drawn in chapter 6, and the need for further studies is presented.

2 District Heating in Finland

District heating (DH) is a service in which heat produced in large production facilities is transferred through a network to meet the distributed but local heat loads. The heat loads typically consist of customers in residential, commercial and public sectors, which use DH for space heating, water heating, and low-temperature industrial purposes. (Frederiksen & Werner, 2013). The large production facilities enable higher production efficiencies than what would be achieved by distributed local heat production (Woods & Overgaard, 2015). Furthermore, the plants may utilize low-cost energy resources which could not be used in the local production. Using local fuel or heat resources that would otherwise be wasted to meet the heating demand of local heat loads is the fundamental idea of district heating. (Frederiksen & Werner, 2013).

Historically, the development of DH has gone hand in hand with combined heat and power production (CHP) (Woods & Overgaard, 2015). In CHP, the excess heat from thermal power plants is utilized for heat production instead of wasting it by condensing. Other commonly used local heat and fuel resources include heat from waste incineration, waste heat from industrial processes, large boilers using bulky fuels that could not be used in small local-scale boilers (including most combustible renewables) and low-temperature heat sources such as geothermal. (Frederiksen & Werner, 2013). The energy resources must have low costs due to the high investment costs in network infrastructure. Also, the cost differential compared to other heating forms has to suffice the network heat loss related costs. To minimize these distribution-related costs, dense urban structures are required. (Woods & Overgaard, 2015).

2.1 The Market

District heating competes in the low-temperature heat markets. The customers in these markets include mainly residential, service, and low-temperatures using industrial and agricultural actors (Frederiksen & Werner, 2013). As a result of the heavy investment needs in network infrastructure and the clear economies of scale, DH as a service can be defined as a natural monopoly (Sandoff & Williamsson, 2015); (Frederiksen & Werner, 2013). On the other hand, the heating markets in Finland are deregulated and competitive. This means that the customers have the liberty to choose their heating type per se and that there is no specific legislation considering the choosing or pricing of heating or heating type. (Finnish Energy, 2019).

However, the natural monopoly state has led to clear market power for DH within the heat markets. Though the customers can change their heating type to other forms of heating, this may be cumbersome and include notable upfront costs (Frederiksen & Werner, 2013). Due to the market power, the Finnish Competition and Consumer Authority oversee that the price level and the price increases are reasonable and in line with the expenses. (Finnish Competition and Consumer Authority, 2014).

DH is the most used heating type in Finland with a market share of 46% of heating in residential and service sectors in 2018. Furthermore, according to Finnish Energy, it is the most commonly chosen heating type in new buildings. (Finnish Energy, 2019). DH is currently provided in almost 170 Finnish municipalities and covers practically all urban areas of Finland (Motiva, 2019). Maintaining a high market share in the current market areas is crucial to DH due to the heavy investments and the long-term nature of the business. The long-term nature also reduces the ability of the business to change along with the markets. Therefore, the long-term planning stage, including the investment decisions in the network and production infrastructure, is extremely important to the DH provider in maintaining the competitive edge compared to the competing types of heating. (Sandoff & Williamsson, 2015).

The competing types of heating include e.g. local-scale oil boilers and firewood, direct electric heating, and heat pumps. The market share of oil boilers has been decreasing rapidly during recent decades, whereas the market share of local-scale heat pumps, including ground source and air-source heat pumps, have been increasing. (Statistics Finland, 2018). Local-scale heat pumps can be seen as the main competitor for DH in the heating sector in the future. Compared to the other heating types, the benefits of DH for the customers include easiness due to low maintenance need and reliability due to firm back up capacity during the peak load conditions. Furthermore, DH does not require high upfront investments by the customer and provides heat at a predictable price. (Frederiksen & Werner, 2013); (Woods & Overgaard, 2015). The development of the market shares of different heating types is presented in Figure 1.

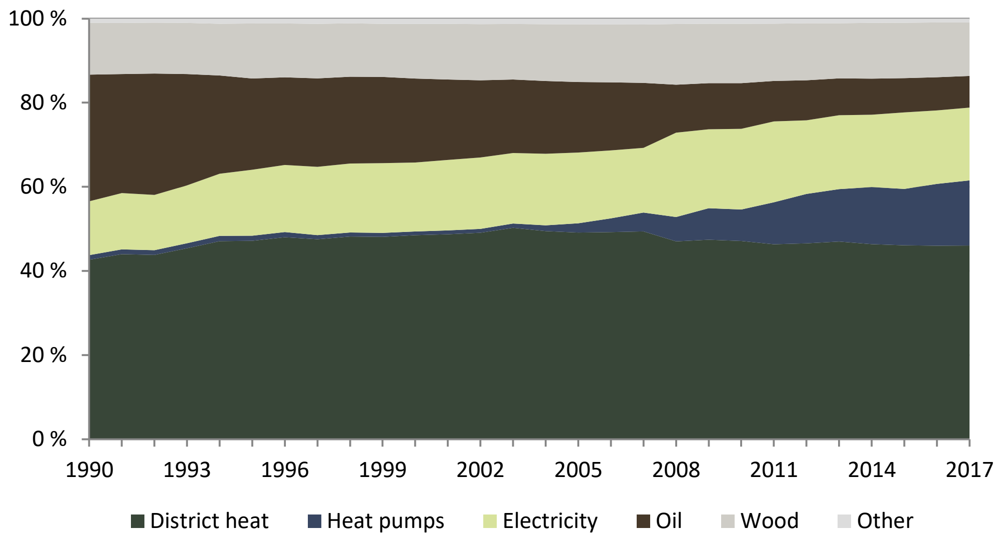

Figure 1. Net effective heating energy of residential, commercial and public buildings by energy source proportions. Data source: (Statistics Finland, 2018).

The traditional attributes of DH include e.g. economy-of-scope, economy-of-size, and flexibility. The economy-of-scope refers to the joint production of heat and something else. Usually, this leads to cost savings compared to heat production only. This means not only CHP but also waste incineration and combustion of “waste” biomass, such as forest industry residuals, as well as utilizing waste heat. Economy-of-size means that the larger boilers and other production facilities usually have smaller specific costs than the local small-scale production technologies. Flexibility refers to the fact that DH systems can change the heat source according to prevailing market conditions, which is usually not possible in local-scale production. Furthermore, compared to local-scale production, DH usually has a lower environmental impact and better security of supply due to lower primary energy consumption, more enhanced emission treatment and domestic fuels used. (Frederiksen & Werner, 2013).

In the new market situation with local-scale heat pumps challenging DH, some of these attributes are not as clear advantages for DH as they were in the past. The marginal costs of the increasingly commercialized heat pumps have decreased alongside the development of their coefficient of performance (COP), decreasing the advantage of the economy-of-size for DH. Though the heat pumps require electricity as their power source, the greater share of their input energy comes from the environment, which is free of charge. Therefore, heat pumps are not that exposed to market risks either. The heat pumps may even have a less environmental impact and provide relatively good security of supply due to the increasing amount of utilizable domestic electricity production and the high share of ambient energy used in heat production. (Sandoff & Williamsson, 2015).

Consequently, local-scale heat pumps provide low-marginal cost environmentally-friendly heat, having though relatively high investment costs. These characteristics are very much the same as the ones for DH. Furthermore, the customer may not even have to bear the risk of the investment, as there are already service providers in the market taking care of it, leaving the customer only to pay a service fee, much like in DH. Local-scale heat pumps also enable the customer to tender a majority of the costs, including the heat pump and the energy component of electricity, whereas tendering with DH is limited to the heat exchanger only.

The production of DH has been to a large extent dominated by fossil fuels. Still in 2018, coal, peat, natural gas and oil accounted for more than half of the fuels used in DH production in Finland. Biomass has increasingly replaced fossil fuels during the 2010s. Altogether, the heat produced by combusting fuels accounted for 90% of the total production. The heat produced by waste heat and heat pumps accounted for approximately 10%, of which the heat pumps accounted for approximately 3%. The total DH production in 2018 was 37.1TWh, whereas the consumption was 33.5TWh. (Finnish Energy, 2019). The difference in the numbers marks the network losses.

The DH demand has been steadily increasing for several decades but the demand growth has been slightly slowing down recently. The predictions made by the Ministry of Economic Affairs and Employment states that DH consumption would be close to the current level still in 2030 (TEM, 2017). In the short term, the district heating demand is largely dependent on the temperature level. Hence, normalization is needed to compare the DH demand between different points of time and locations.

The main drivers for DH demand increase in the longer term are urbanization and new building. The main drivers for decreasing DH demand are energy efficiency measures and switching to other heating sources, such as heat pumps. (Sandoff & Williamsson, 2015). However, the switching of heating types happens also vice versa and is especially evident in the form of switching from oil heating to DH. The historical fuel usage in DH production by fuel type proportions and the demand development of DH is presented in Figure 2.

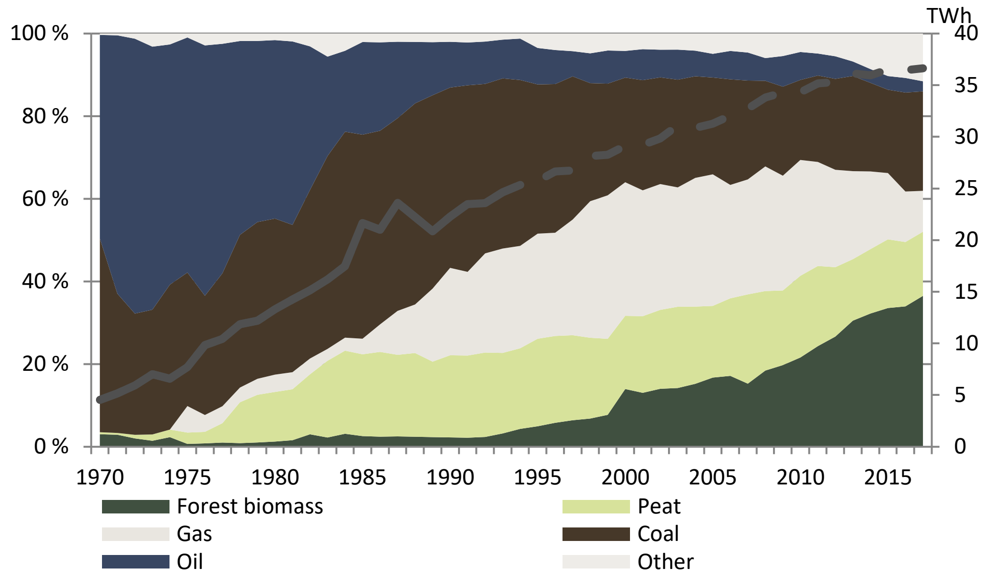

Figure 2. Fuel usage by fuel type proportions in DH production and total demand in 1970-2017. The demand in 1970-1994 is actual demand and the demand from 1995 is temperature corrected with population-weighted average heating degree days in Finland and assumed 70/30 share in space heating/hot water. Data sources: (Statistics Finland, 2018), (FMI, 2019).

2.2 Network and Demand

The DH network consists of insulated pipes that deliver hot medium from the production facilities to the end-users. The network usually covers the central areas of a city or municipality, where the buildings are more densely built enabling a proper amount of heated buildings per unit of pipe length to make the investment profitable. (Frederiksen & Werner, 2013); (Woods & Overgaard, 2015). The total length of the Finnish DH network is 15 140km (Finnish Energy, 2019). The most commonly used pipe system for DH is a two-pipe system consisting of a supply pipe and a return pipe. In the Finnish systems, the medium (water) in the network is pressurized to prevent it from boiling at operating temperatures. In some other countries, also water in the form of steam is used. (Frederiksen & Werner, 2013); (Woods & Overgaard, 2015).

The supply water temperature in the Finnish systems varies between 70-120°C (Finnish Energy, 2014). To reduce the heat losses, the supply water temperature should be as low as possible. The required supply temperature in a network depends e.g. on the pipe diameters, network length and the dimensioning of customer equipment. At a minimum, the supply water temperature must exceed tap water temperature plus the heat exchanger pinch temperature even at the most remote customers. Typically, the hot tap water temperature is around 55°C. (Frederiksen & Werner, 2013). The temperature has to be higher than this if the customer's heat exchanger is designed for higher supply temperatures, which is often the case in the existing networks. An estimation of the supply temperature in average Finnish DH systems can be presented as in Equation (1) (Finnish Energy, 2014). The estimation is also used in the modeling of this thesis.

$$If\ t_a > 8°C, then\ t_{supply} = 70°C, else$$
$$t_{supply} = 115°C + (t_d - t_a)\frac{45°C}{8°C - t_d} \tag{1}$$

where

t_a	the outdoor air temperature	[°C]
t_d	the dimensioning temperature in the chosen area	[°C]

The new generation heat networks in new residential areas are designed with lower supply temperatures to reduce the heat losses in the network and heat storages, and to increase the efficiency of several heat production technologies, such as heat pumps, CHP, and flue gas condensation (Averfalk & Werner, 2017). Lowering the temperature levels significantly in the existing networks could lead to bottlenecks in the system due to insufficient pipe diameters and temperatures to fall below the limits at customers' substations due to insufficient heat exchangers and long transport distances. (Frederiksen & Werner, 2013); (Sipilä, 2015).

Due to the heavy initial investments in the networks, it is usually not feasible to replace the existing infrastructure to achieve the lowered temperatures. (Frederiksen & Werner, 2013). However, the decrease in heat consumption due to energy efficiency measures in renovated existing buildings and new buildings in surrounding areas may enable lower temperatures at least in some parts of the existing networks as well (Averfalk & Werner, 2017).

The network is controlled by changing the temperature difference or changing the water flow in the system. The supply water temperature is controlled by the production plants according to the outdoor temperature. Concurrently, the sufficient pressure difference between supply and return pipes are maintained with pumps in the network. Customer substations control the water flow through customer heat exchangers. The return water temperature depends on how well the heat exchangers operate. For these reasons, high supply temperatures are required to maintain sufficient temperature difference at the customer end if the heat exchangers are old. (Frederiksen & Werner, 2013); (Woods & Overgaard, 2015).

Connections to the customers are arranged through heat exchangers, usually one for space heating and one for tap water heating purposes. The heat demand for space heating purposes almost linearly depends on the outdoor temperatures. This is due to the linear dependency between heat losses from the buildings and the outdoor temperatures. However, this linear dependency only applies to outdoor temperatures below approximately 17°C, after which heating is usually not needed anymore. At this temperature, the solar gains and waste heat from household appliances are usually sufficient to fill the rest of the demand to reach a comfortable indoor temperature. (Frederiksen & Werner, 2013).

On the other hand, the demand for tap water heating is mostly dependent on the time of the day and the day of the week, and not directly of the outdoor temperature. However, the demand for hot tap water varies also seasonally, being at its highest during the winter and at its lowest during summer. This is an indirect consequence of consumer habits, e.g. of taking warmer showers during the periods of colder outdoor temperatures. (Frederiksen & Werner, 2013).

The total heat load of a DH network mainly consists of the aforementioned demand components as well as the network losses. The share of hot tap water is approximately 30%, distribution losses 5-10%, whereas space heating accounts mostly for the rest. Minor load impacts are caused by wind chill, solar gains, and appliance waste heats. (Frederiksen & Werner, 2013).

In this thesis, the heat load profile is divided into two components: a fixed component and a weather dependent component. The fixed component represents tap water heating and covers 30% of the total heat load. The weather-dependent component represents space heating and network losses and is based on the hourly outdoor temperature in Jyväskylä in 2014. In the profile, the load is outright weighted with the outdoor temperature, except that when the temperature exceeds 17°C, no DH is used for space heating. The same method was used by (Värri & Syri, 2019). This component comprises 70% of the total heat load.

The total demand is a simple summation of these two profiles. The profile neglects the seasonal and hourly variations in hot tap water demand and does not accurately represent the distribution losses. Even so, the profile will provide a good basis for the analysis made in this thesis. The demand profile and the duration curve for the modeled network are presented in Figure 3.

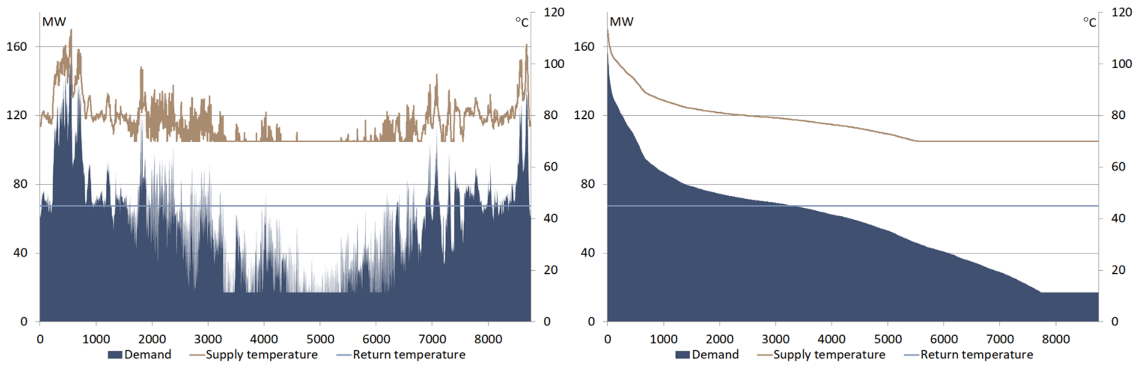

Figure 3. Demand profile and temperature levels for the example network based on outdoor temperature data for Jyväskylä in 2014 and Equation (1). Data: (FMI, 2019).

2.3 Production Technologies

In general, DH production can be divided into base load and peak load production. The characteristics of the base load production include high investment costs and low variable costs. Therefore, base load capacity should be utilized in heat production as much as possible to decrease the total production costs. Peak load production capacity, on the other hand, has to be built to fulfill the demand during the peak load hours and to minimize the need for costly base load capacity. (Frederiksen & Werner, 2013); (Sipilä, 2015).

Also, peak load capacity may be used as reserve capacity if base load capacity for some reason is not available. A typical scheduled period of this kind of production is during the summer when the base load production plants have their maintenance break or if the network heat load is below the minimum load of the base load plant. (Sipilä, 2015). However, the maintenance breaks are not considered in this study and the network minimum load stays above the base load minimum capacity. The characteristics of peak load production include low investment costs and high variable costs (Frederiksen & Werner, 2013).

The optimal base load capacity depends on the total fixed and total variable costs of the chosen base and peak load technologies. Usually, the base load capacity covers more than half of the peak demand and represents more than 90% of the yearly energy demand. (Frederiksen & Werner, 2013); (Sipilä, 2015). The principle of base and peak load production is presented in Figure 4.

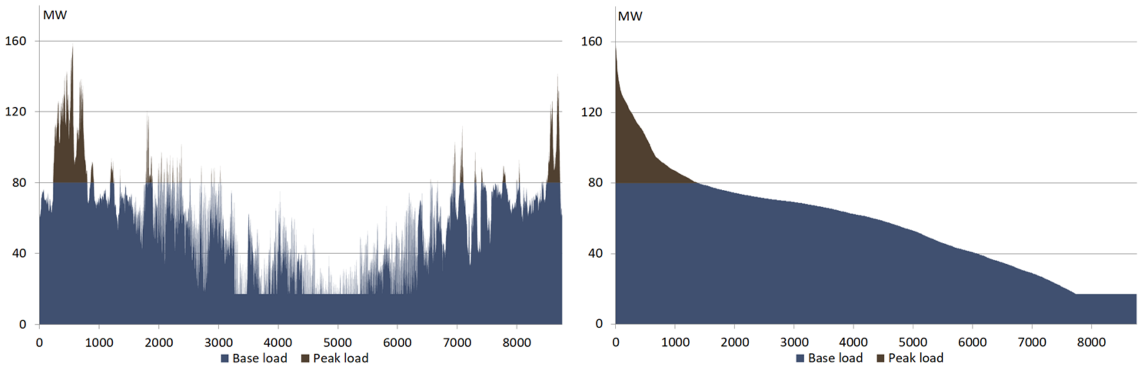

Figure 4. The principle of the division between base and peak load production in a DH network.

It is possible to calculate an optimal amount of base load production in a DH system if the duration curve of the heat demand and the fixed and variable costs of the production technologies are known. First, an approximation in the form of a function has to be made out of the duration curve. The function has hours as a variable and gives out capacities in megawatts. The same principle was used by Fredriksen and Werner (2013). The optimal amount of base load capacity may then be calculated as:

$$\Phi_{base} = f\left(\frac{F_{base} - F_{peak}}{V_{peak} - V_{base}}\right) \tag{2}$$

where

F_{base}	the fixed yearly costs of base load including investment annuity and fixed O&M costs per production capacity, EUR/MW
F_{peak}	the fixed yearly costs of peak load including investment annuity and fixed O&M costs per production capacity, EUR/MW
V_{base}	the variable costs of base load including fuel and variable O&M costs per produced heat, EUR/MWh
V_{peak}	the variable costs of peak load including fuel and variable O&M costs per produced heat, EUR/MWh.

In this study, several different base load and peak load technologies are considered. To simplify the comparison, an average of the optimal base load capacities with different technologies is used in the modeling. The amount of base load used in the modeling is

80MW, whereas the peak load capacity is 78MW. The yearly peak demand of the modeled network is 158MW.

Usually, the network also includes other heat only production with low fixed costs as reserve capacity. This capacity may be used in the case of a sudden breakdown of the base load units. Altogether, the installed peak/reserve load capacity is usually large enough to meet the heat demand even at the peak load periods. The reserve capacity usually consists of liquid or gaseous fuel boilers, which are less investment heavy than solid fuel ones. (Frederiksen & Werner, 2013).

2.3.1 Combustion Technologies

Combustion technologies are the dominating production types in the Finnish DH systems. The combustion technologies can be divided into combined heat and power production (CHP) and heat only boiler stations (HOB). In practice, CHP usually is the base load production technology, whereas HOB plants have been used for peak load production. HOB is currently used as base load production mainly in smaller networks (total volume less than 100GWh). Proportional sourcing of heat per source type and the total sourcing volume of the Finnish DH suppliers is presented in Figure 5. Purchase heat mostly consists of third party CHP production.

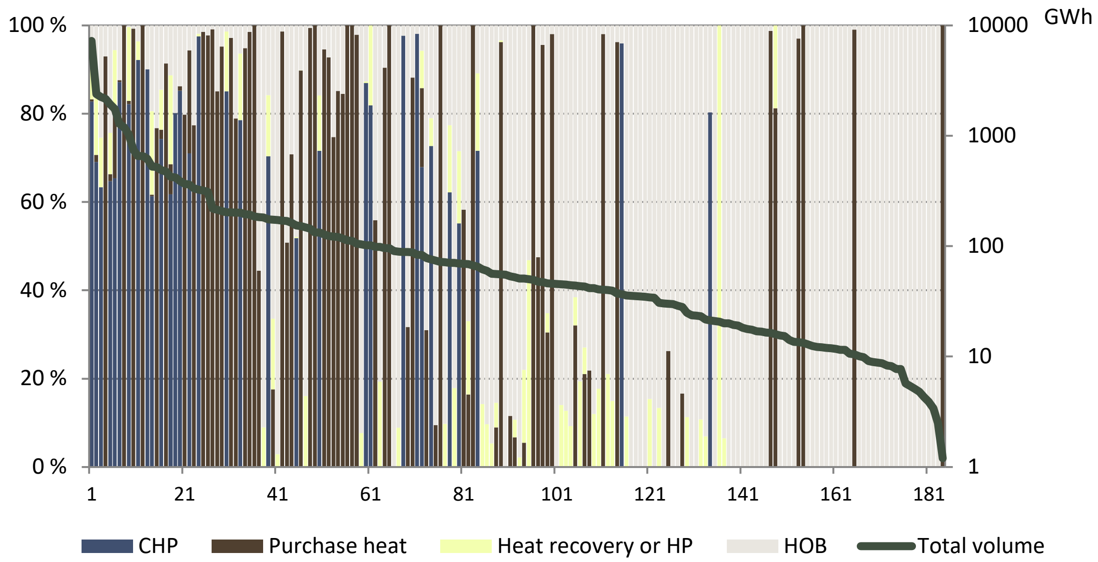

Figure 5. The Finnish DH suppliers and their sourcing of heat per source type and the total sourcing volume of each network (green line). Each vertical bar represents one DH supplier. Data source: (Finnish Energy, 2019).

The capacity weighted average ages of the existing CHP and HOB plants in Finland are 29 and 28 years, respectively. With an estimated average lifetime of 40 years for CHP plants, approximately 50% of the existing CHP plants will be replaced within the next 10 years. Thus, many replacement investments in the base load production will be made in the near future. The price level of electricity will be one of the main factors determining whether CHP or HOB will be the preferable combustion based technology for the upcoming investments. The age structure of the existing heat production capacity in Finland is presented in Figure 6.

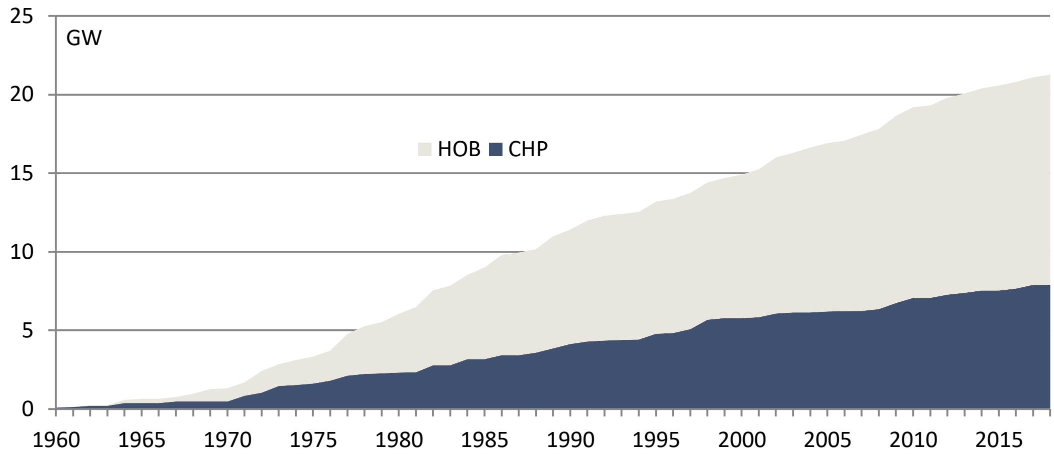

Figure 6. The cumulative heat production capacity of existing CHP and HOB plants in 1960-2019. Data source: (Finnish Energy, 2019).

2.3.1.1 Boiler Technologies and Heat Only Boilers (HOB)

A boiler is a device for heat production in the form of hot water or steam by fuel combustion. If the only final product of the plant is heat, e.g. in DH, the boiler is called a heat only boiler (HOB). The boilers can be designed for liquid or solid fuel combustion. The design for liquid fuel boilers can be fairly simple, leading to very low investment costs. Usually, these boilers use fossil fuels, such as conventional oil and gas. Thus, if used as heat only boilers in DH, they are used as peak and reserve capacity due to the higher marginal costs of the fuel. (Frederiksen & Werner, 2013). In the future, bio-oils and biogas may also be utilized in these boilers, though these fuels are still also relatively expensive (Sipilä, 2015).

Boilers combusting solid fuels are slightly more complex and expensive but enable the utilization of less expensive fuels (Sipilä, 2015). The complexity of the combustion depends on the chemical and physical properties of the solid fuel. The chemical properties may cause a risk for corrosion, e.g. chloride in the fuel may form corrosive sulphuric acid in the combustion process. The physical properties include e.g. the moisture content of the fuel and how homogenous the fuel is, and has an impact on the combustion easiness. (Frederiksen & Werner, 2013).

Pulverizing boilers are usually used for combustion of coal. The coal is first pulverized, after which it is injected into the boiler together with the combustion air. They can even be used for wood and peat combustion, but the fuel has to be rather dry at a moisture content of approximately 15%. Thus, using e.g. forest biomass would require the fuel to be dried significantly, as the fuel often comes at moisture content around 50%. Also, the fuel must be relatively homogenous, which excludes municipal waste combustion in pulverizing boilers as well. The advantages of pulverizing boilers include fast alternation of the load. (Frederiksen & Werner, 2013); (Sipilä, 2015).

Higher flexibility considering the moisture content and type of solid fuel is achieved with fixed and fluidized bed boilers. Fixed bed boilers, also known as grate boilers, are probably the simplest type of solid fuel boilers. In grate boilers, the fuel is placed on a grate, which moves horizontally while burning. The combustion air is injected from above and underneath the grate. Today, grate boilers are the most common boiler type for biomass and waste combustion in smaller plants. The disadvantages of grate boilers include lower efficiencies due to high excess air amounts and less homogenous combustion. (Frederiksen & Werner, 2013); (Sipilä, 2015).

For larger plants, fluidized bed boilers provide a better alternative. In fluidized bed boilers, the fuel is burned in a fluid-like state together with bed material, often sand. Combustion air is supplied underneath the fuel and bed material supply. The main goal of the design is to reduce the emissions exiting the boiler, such as ash, SO_2, and NO_x, and thus reducing the need of costly flue gas cleaning. The disadvantages for this design include e.g. the more cumbersome operation at partial-load. Operation at partial load is possible, but it increases the complexity of the design somewhat. (Frederiksen & Werner, 2013). Fluidized bed boilers are the most common boiler type for new large boiler investments, and are thus the technology studied in this thesis.

In all of the aforementioned boilers, some kind of flue gas cleaning is needed. The cleaning includes three phases, deNO_x, dust removal, and desulphurization. The requirement for these phases depends on much of the chosen fuel and boiler type. It is also possible to build a flue gas cleaning system that does flue gas condensing at the same time. The layout of such a system may vary. One example of this kind of system would first include a dust remover, after which the flue gas enters scrubbers. In the scrubbers, water is sprayed and recycled through polymeric elements together with necessary chemicals to remove harmful compounds from the flue gas. In parallel, the moisture in the flue gas is condensed on the surface of the polymeric elements, after which the water is collected and cooled down in a heat exchanger. Then, the cooled water is sprayed again through the flue gas. (Frederiksen & Werner, 2013).

In DH, the heat recycled in the flue gas condenser is usually used for heating the return water before it enters the boiler. To operate, the moisture content of the flue gas must be high enough. Therefore, flue gas condensers usually require relatively moist fuel to be used. Also, the temperature of the cooling water (in DH the return water), must be low enough. Otherwise, the dew point of the flue gas is not reached and the condensation will not happen. (Frederiksen & Werner, 2013); (Sipilä, 2015).

The more advanced solid fuel boilers with lower marginal costs can be used as heat only boilers in base or intermediate load DH production. Wood-based biomass is the most typical low-cost fuel used in Finland (Finnish Energy, 2019). In waste incineration, municipal waste is used as fuel. The complexity of municipal waste as fuel increases the investment costs of the plant somewhat. However, as the municipal waste usually has negative costs as a fuel, the plants fit very well for priority base load DH production. However, the acceptability of waste incineration in the future is unsure, as it legitimizes high waste production in society. (Frederiksen & Werner, 2013). Instead of a technology “lock-in” in waste incineration, many actors see that wastes should be reduced and the materials re-cycled more broadly.

The main advantage of HOB plants is their low investment costs. The boilers feeding DH systems are usually from 1MW upwards (Khartchenko & Kharchenko, 2014). Thermodynamically the HOB plants feeding the DH system are quite non-ideal, as high exergy fuel is converted into low temperature and low exergy heat. This means that a lot of the potential of the fuel is lost. However, the efficiencies of the HOB plants are usually high and reach close to 1 even in the most basic plants. Furthermore, if a flue gas condenser is used, the efficiencies may even reach 1.2 or higher, depending on the fuel and its moisture content. This is because lower heating value (LHV) for fuels is used in Europe, which does not cover the latent heat consumption in fuel combustion. However, as the flue gas condenser recycles this latent heat from the flue gas, efficiencies higher than 1 may be reached. (Frederiksen & Werner, 2013).

2.3.1.2 Combined Heat and Power (CHP)

Combined heat and power (CHP) production means that both heat and electricity are produced in parallel. The two most common thermodynamic cycles used for large CHP plants include Brayton, an open cycle, and Rankine, a closed cycle. Usually, CHP refers to combustion-based boiler technologies. However, if a closed cycle, such as Rankine cycle is used, the heat source could be something else as well, such as nuclear or high-temperature geothermal heat. Both cycles include a turbine and a generator to produce electricity. In this process, the high exergy part of the energy source is shaved and utilized. The remaining low exergy heat is then utilized in heat production. The high value of electricity has historically provided low-cost heat as a secondary product. (Khartchenko & Kharchenko, 2014); (Frederiksen & Werner, 2013); (Sipilä, 2015).

The Brayton cycle can be easily used for gaseous or liquid fuels, of which natural gas is the most typical one. In the cycle, combustion air is taken in with a compressor. After this, heat is added to the compressed air through fuel combustion in the combustion chamber. The combustion gas is then expanded in a turbine, which in turn runs the compressor and power generator. As not all heat can be extracted in the turbine due to the ambient pressure level, a significant amount of heat is still left in the exhaust gas. If only electricity is produced, this exhaust gas would be led to the atmosphere and thus be wasted. Therefore, the cycle is called an open type. (Sipilä, 2015); (Khartchenko & Kharchenko, 2014); (Frederiksen & Werner, 2013).

However, if there is a nearby demand for heat, such as DH, this heat in the exhaust gas may be recovered with heat exchangers, leading to higher total efficiencies by combined electricity and heat production (Khartchenko & Kharchenko, 2014). The advantage of CHP production with the Brayton cycle is the low impact of heat recovery on the amount of electricity produced. This is due to the constant ambient pressure level at the stack exit and the relatively low pressure losses in the added DH heat exchanger. Thus, the back pressure at the turbine exit does not increase much. In addition to gaseous and liquid fuels, also solid fuels may be used in more advanced designs, such as pressurized fluidized bed boilers. However, this kind of technology has not had a breakthrough in the markets. (Frederiksen & Werner, 2013).

As mentioned, the Rankine cycle is much more flexible regarding the heat source. This is due to the closed type of cycle. Most commonly, combustion boilers, similar kinds as introduced in the previous chapter, are used as a heat source. The only requirement of the boiler is the ability to produce high temperatures. It is even possible to utilize the waste heat of the Brayton cycle due to the high temperature of the exhaust gas, leading to an efficient combined cycle. The conventional circulating medium in the Rankine cycle is water, and the cycle can thus also be called a steam cycle. In the cycle, water is pumped to a series of heat exchangers in the boiler. In the heat exchangers, the pressurized water is heated up into high temperature and high-pressure steam. The steam is then expanded to lower pressure in one or more turbines, producing work while rotating the turbines and an electricity generator. In a conventional steam power plant, the saturated steam after the turbine is condensed in a cold condenser, usually at ambient temperature level, before entering the feed water pumps and continuing the cycle. A cold condenser means lower pressure at the turbine exit, leading to a greater pressure drop in the turbine and thus higher electricity production. (Frederiksen & Werner, 2013); (Sipilä, 2015).

In CHP production, the condenser is replaced with a heat exchanger. The heat exchanger may heat for example DH return water. The higher condensing temperature causes a pressure increase in the turbine exit, leading to slightly less electricity produced. This kind of design is called a back-pressure CHP plant. Back-pressure refers to the higher pressure level at the turbine exit. In case of a high demand for heat, the turbine may also be by-passed to increase heat production by the cost of lost power production. This requires a by-pass valve to be placed before the turbine. (Frederiksen & Werner, 2013); (Sipilä, 2015). The principle of a most simple Rankine cycle based DH producing CHP plant is illustrated in Figure 7.

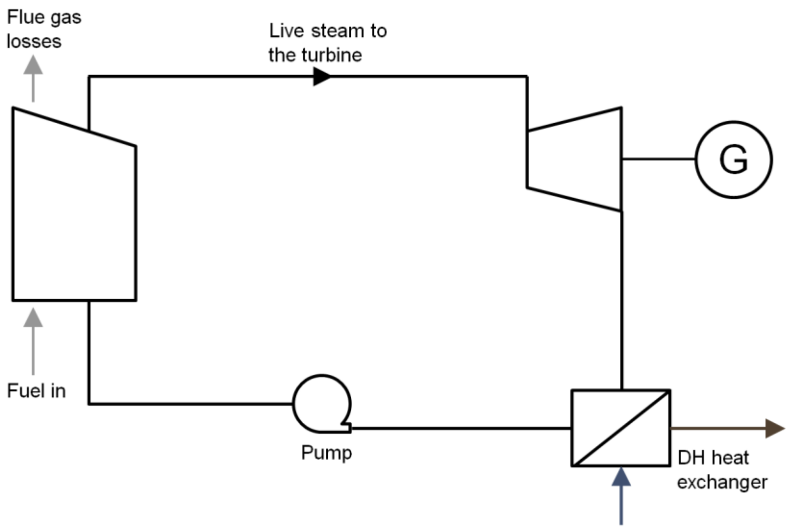

Figure 7. A simple Rankine cycle based DH producing CHP plant. Based on (Khartchenko & Kharchenko, 2014); (Frederiksen & Werner, 2013).

The downside with back-pressure CHP plants is that it has to be operated according to heat demand, and is thus relatively inflexible regarding the electricity production. If auxiliary cooling is possible, e.g. dumping heat to the sea, operating above this would also be possible. However, an unnecessary large amount of heat would be wasted in the back-pressure operation. (Sipilä, 2015).

In terms of power production, a more flexible type of CHP plant would be the extraction-condensing CHP plant. Such a design has an additional low-pressure turbine and a cold condenser. In case of low heat demand or high electricity demand, the plant could partly or fully skip the heat exchanger, and instead lead the steam to the low-pressure turbine and the cold condenser. This kind of operation would lead to slightly higher electricity production and represent the same principle as conventional steam power plants. (Frederiksen & Werner, 2013); (Sipilä, 2015). However, the design increases the specific capital costs of the plant and would require high cooling water availability in condensing operation (Sipilä, 2015). As the target of this thesis is to study DH production and not electricity production, the chosen CHP design for the modeling represents the back-pressure type. The operating areas of both back-pressure and extraction-condensing designs are illustrated in Figure 8.

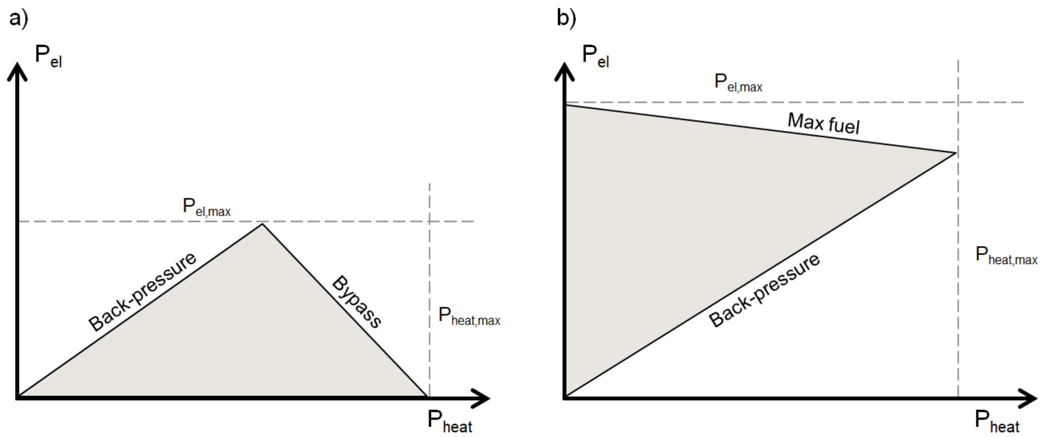

Figure 8. The operating areas of a) back-pressure CHP plant and b) extraction-condensing CHP plant. Modified from Dahl et al. (2019).

In case of increasingly volatile electricity prices in the future, the traditional CHP technologies presented above may also be partly replaced with more flexible motor CHP plants. The fuel used in these plants would be either liquid or gaseous fuels, and thus the operating cost would be higher than the ones for solid fuel based plants. Consequently, the profitability of these plants would be highly dependent on the benefits of utilizing volatile electricity prices in the market. (Sipilä, 2015). As the electricity price volatility is assumed to increase fairly moderately (see 3.2.2), the motor CHP plants will be excluded from the further analysis in the study.

Traditionally, the production of DH in Finland has been dominated by CHP. Still in 2018, the share of CHP production of the total delivered heat was over 70% (Finnish Energy, 2019). The reasons behind this are both historical and economical. Historically, electricity has mostly been produced by steam power plants. Constructing a DH network and utilizing the waste heat produced by the plants has therefore increased the system efficiency (Sipilä, 2015). Though heat has been the second priority in the production in the past, it may be considered the priority in the new plant investments.

Due to the integrated electricity markets, local electricity production is not compulsory. It is only beneficial if it is competitive against the other electricity production in the market. On the other hand, the local DH system requires heat. As the income from electricity is decreased due to the competition with low marginal costs wind, nuclear and hydropower in the market, the benefit of CHP is also decreased. The correlation between heat demand and wind power production may also further decrease the capture price for CHP in the markets (Dahl, et al., 2019). A sub-goal of this thesis is to find out, whether CHP or the less investment heavy HOB would be the preferred technology if combustion based technologies are chosen.

2.3.2 Non-combustion Technologies

As it can be noted from Figures 2 and 5, the non-combustion technologies are currently very marginal in the Finnish DH production. However, the share of the technologies has been significantly increasing during the 2010s. The trend is most likely to continue in the coming decades.

2.3.2.1 Heat Pumps

Heat pumps are an interesting alternative to replace heat production by combustion as they mostly utilize a low quality and low-temperature heat source that is available with low or no cost from the environment or would otherwise be wasted. Thus, they provide an environmentally friendly heat production complying well with the traditional attributes of DH presented in 2.1. They can be driven either mechanically by compressors or by thermal energy as in absorption heat pumps. (Bach, 2014); (Frederiksen & Werner, 2013).

The mechanical or compression-driven heat pumps consume electricity to drive a compressor. The other main components in a compression-driven heat pump are the evaporator, condenser and an expansion valve. The cycle configuration of a simple one-stage heat pump process and the principle sketch of a temperature heat load diagram are presented in Figure 9. In the simplest operational cycle, a chosen refrigerant is first evaporated in the evaporator (4-1), in which heat from a heat source is added to the process. The refrigerant in vapor form is then compressed from the evaporation to the compression pressure in the compressor (1-2), after which the compressed vapor condenses in the condenser (2-3). During the condensation process, the compressed refrigerant releases heat to the heat sink, in DH case the supply water. After the condenser, the pressure of the refrigerant is lowered with the help of the expansion valve (3-4). (Jensen, et al., 2018).

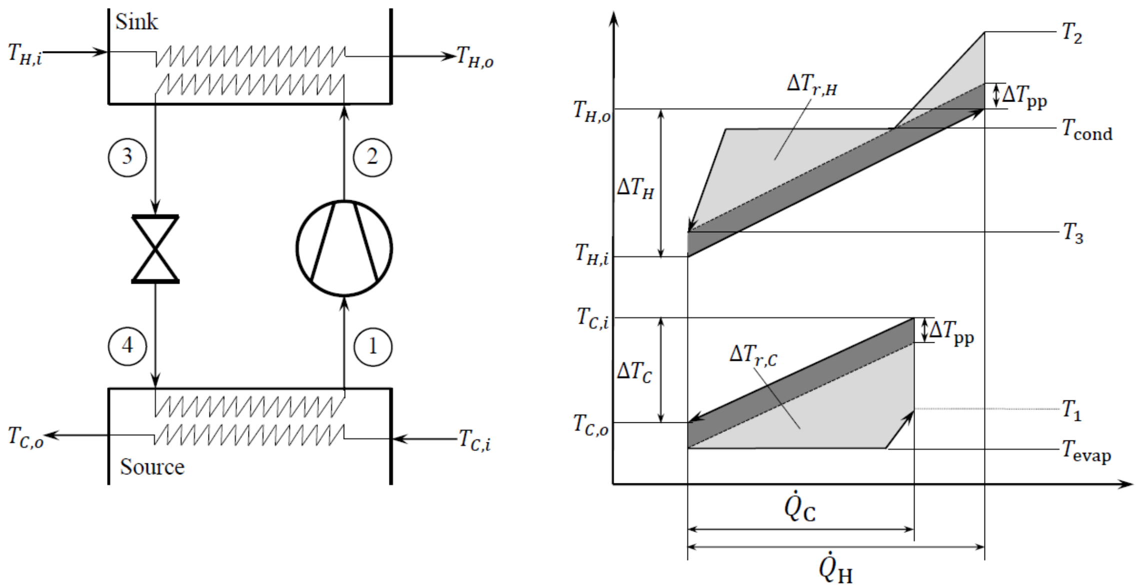

Figure 9. Cycle configuration of a simple one-stage heat pump process and the principle sketch of a temperature heat load diagram. Source: (Jensen, et al., 2018).

In reality, the cycle of the mechanical heat pump can be more complex than this. For example, the compression of the refrigerant may be divided into two phases to increase cycle efficiency (Bach, 2014). Figure 9 shows that the temperature of the source decreases in the operation. Thus, if cold would be needed, the operation could be the opposite as well, with a hot source and a cold sink. This kind of device is called a chiller. Chillers are much more widely utilized globally than heat pumps. If both heating and cooling are needed, the same device could even function as a chiller and a heat pump at the same time. (Frederiksen & Werner, 2013). Thus, the benefits of heat pumps would significantly increase in the case of a district heating and cooling (DHC) system instead of a DH only system. In DHC, return cooling water would act as a heat source for heat production. However, DHC is not within the scope of this thesis.

The absorption-driven heat pumps utilize high-temperature heat to extract heat from a lower temperature source. In this way, there is no need for a compressor in the thermodynamic cycle. Instead, a pump can be utilized to raise the pressure of the refrigerant. As pumps consume much less electricity than compressors, a large amount of electricity will be saved. (Frederiksen & Werner, 2013); (Bach, 2014). However, usually, the high-temperature heat is produced by combusting fuels (Frederiksen & Werner, 2013). In this thesis we are trying to find an alternative for combusting, so the compression-driven heat pump turns out to be a better option for further analysis. Furthermore, the compression driven heat pump connects the heating sector to the power sector and provides valuable flexibility to both sectors (Nielsen, et al., 2016). The compression driven heat pumps are also currently dominant in the heat pump markets (Jensen, et al., 2018).

A major factor in the economic feasibility of large-scale heat pumps is the low operating costs originating from a higher coefficient of performance (COP) (Jensen, et al., 2018). The COP of a heat pump is defined according to Equation (3) (Bach, 2014).

$$COP = \frac{\dot{Q}_{out}}{\dot{W}_{in}} \tag{3}$$

where

$\dot{Q}_{out}$ the heat produced by the heat pump
$\dot{W}_{in}$ the input power to the heat pump.

In the equation, $\dot{W}_{in}$ is considered as the only input energy to the heat pump. In mechanical heat pumps this is the compressor electricity consumption. The low-temperature heat source is considered to be free and is excluded from the equation. The COP of the DH producing compression driven heat pumps usually varies in the range of 3-6. However, the higher COPs of the heat pumps may only be achieved if there is an accessible relatively high-temperature heat source, or if the supply temperatures of the network are low. (David, et al., 2017); (Arpagaus, et al., 2018).

In the existing networks, the supply temperatures are usually higher, leading to lower COP values. Higher COP values could be achieved by locating the heat pumps in the distribution parts of the DH network instead of the transmission lines of the network. (Bach, et al., 2016). Furthermore, developments in the future generation networks may lead to lower supply temperatures, and thus higher COP values (Averfalk & Werner, 2017).

The theoretical maximum COP for a heat pump is described as Carnot efficiency. This maximum is also highly dependent on the temperature difference between the hot sink (supply water in DH case) and the cold source (the chosen heat source). The Carnot efficiency for a heat pump can be calculated with Equation (4) (Bach, 2014).

$$COP_{Carnot} = \frac{T_H}{T_H - T_C} \tag{4}$$

where

T_H	the temperature of the hot reservoir (sink)	[K]
T_C	the temperature of the cold reservoir (source).	[K]

However, as the temperature of the hot and cold reservoirs changes when passing the heat exchangers in the condenser and evaporator sides respectively, a logarithmic mean temperature may be used instead of a fixed temperature level (Arpagaus, et al., 2018). The theoretical maximum COP calculated in this way is called the Lorentz efficiency. The Lorentz efficiency for a heat pump may be calculated with Equation (5) (Jensen, et al., 2018).

$$COP_{Lorentz} = \frac{\bar{T}_H}{\bar{T}_H - \bar{T}_C} \tag{5}$$

where

$$\bar{T}_H = \frac{T_{H,out} - T_{H,in}}{\ln\left(\frac{T_{H,out}}{T_{H,in}}\right)}$$

$$\bar{T}_C = \frac{T_{C,in} - T_{C,out}}{\ln\left(\frac{T_{C,in}}{T_{C,out}}\right)}$$

In reality, the efficiencies of the heat pumps are significantly lower than the ideal ones presented above (Bach, 2014). This is e.g. due to inefficiencies in the compression, heat transfers in the cycle and the fact that the condensing and evaporating temperatures of the refrigerant in conventional heat pumps are constant and not changing alongside the reservoir temperatures (Jensen, et al., 2018). The latter can be seen from Figure 9. An optimal refrigerant would follow the temperatures of the hot sink and cold source, thus minimizing the light grey area. The pinch temperature, ΔT_{pp}, represents the heat transfer performance of the heat exchangers and marks the heat transfer inefficiencies (Jensen, et al., 2018). Therefore, the final COP of the heat pump is calculated with Equation (6) (Jensen, et al., 2018); (Bach, 2014).

$$COP = COP_{Lorentz}\,\eta_{Lorentz} \tag{6}$$

where

η the Lorentz efficiency (system efficiency) of the heat pump.

The Lorentz efficiency of the system depends on e.g. on the choice of refrigerant, compressor and heat exchanger type. Also, the efficiency of the chosen configuration varies during the year according to temporal heat source and heat sink temperatures. (Pieper, et al., 2019b). Historical levels of the operational temperature levels are usually available for economic evaluation on heat pumps for DH production. On the other hand, the component-specific decisions are less straightforward to estimate. A generalized COP estimation of heat pumps processes was presented by (Jensen, et al., 2018). The proposed estimation method is based on Equation (7).

$$COP = COP_{Lorentz} \frac{1 + \frac{\Delta\bar{T}_{r,H} + \Delta\bar{T}_{pp}}{\bar{T}_H}}{1 + \frac{\Delta\bar{T}_{r,H} + \Delta\bar{T}_{r,C} + 2\Delta\bar{T}_{pp}}{\bar{T}_H - \bar{T}_C}} \eta_{is,c}\left(1 - \frac{w_{is,e}}{w_{is,c}}\right) + 1 - \eta_{is,c} - f_Q \qquad (7)$$

where

$\Delta\bar{T}_{r,H}$	refrigerant induced temperature difference at condenser	[K]
$\Delta\bar{T}_{r,C}$	refrigerant induced temperature difference at evaporator	[K]
$\Delta\bar{T}_{pp}$	entropic average pinch point temperature difference	[K]
$\eta_{is,c}$	compressor isentropic efficiency	
$\frac{w_{is,e}}{w_{is,c}}$	the ratio of isentropic expansion and compression	
f_Q	compressor heat loss.	

Furthermore, the preceding notations may still be approximated as (Jensen, et al., 2018):

$$\Delta\bar{T}_{pp} \approx \Delta T_{pp}$$
$$\Delta\bar{T}_{r,C} \approx \frac{1}{2}\left(T_{C,in} - T_{C,out}\right)$$
$$\Delta\bar{T}_{r,H} \approx a\left(T_{H,out} - T_{C,out} + 2\Delta T_{pp}\right) + b\left(T_{H,out} - T_{H,in}\right) + c$$
$$\frac{w_{is,e}}{w_{is,c}} \approx d\left(T_{H,out} - T_{C,out} + 2\Delta T_{pp}\right) + e\left(T_{H,out} - T_{H,in}\right) + f$$

For the component characteristics above the ranges assumed in the simulations by Jensen et al. (2018) were $\eta_{is,c}$= 0.4-0.9, f_Q= 0.0-0.6 and ΔT_{pp}= 0-10K. The two first represents the performance of the compressor and the last one the performance of the heat exchangers. For the values, (Pieper, et al., 2019b) used the following: $\eta_{is,c}$= 0.8, f_Q= 0.05 and ΔT_{pp}= 5K (Pieper, et al., 2019b). The same values are used in this thesis, as they are assumed to represent well the performance of an average large-scale heat pump.

Refrigerants for heat pumps may be divided into synthetic and natural refrigerants. The synthetic refrigerants have been dominating in the earlier installations in Europe, the most used refrigerant, R-134a, representing more than 90% of the market. However, the synthetic refrigerants are being phased out due to their high global warming potential in case of leakages. As a result, natural refrigerants are taking over. Two natural refrigerants that have already penetrated the market are ammonium (NH_3) and carbon dioxide (CO_2). Of these two refrigerants, ammonium is a better fit for large-scale heat pumps due to the high working pressure requirements of CO_2 appliances. However, the CO_2 based heat pumps can reach higher supply temperatures. (David, et al., 2017).

With the relatively high maximum temperature of 90°C and the aforementioned characteristics, ammonia may be seen as one of the best fits for a refrigerant in DH supplying heat pumps (David, et al., 2017). In subcritical heat pumps such as the ones using ammonia, the maximum temperature is determined by the evaporation temperature of the refrigerant in the pressure that the chosen compressor is able to achieve (Arpagaus, et al., 2018).

A study conducted by Arpagaus et al. (2018) identified over 20 heat pump models from 13 manufacturers that are able to supply at least 90°C. Approximately one fourth of these heat pumps used ammonia as refrigerant, the pumps being also among the largest in terms of heat capacity, the largest being up to $15MW_{th}$ (Arpagaus, et al., 2018). A drawback with ammonia is that it is poisonous, which has to be taken into account in the precautions. (Frederiksen & Werner, 2013). When ammonia is used, the coefficients for linear models for $\Delta\bar{T}_{r,H}$ and $\frac{w_{is,e}}{w_{is,c}}$ will be as presented in Table 1.

	a	b	c
$\Delta\bar{T}_{r,H}$	0.20	0.20	0.016
$\frac{w_{is,e}}{w_{is,c}}$	0.0014	-0.0015	0.039

Table 1. Coefficients for the linear models for $\Delta\bar{T}_{r,H}$ and $\frac{w_{is,e}}{w_{is,c}}$ when ammonia is used as a refrigerant. Source: (Jensen, et al., 2018).

Having the component characteristics for the heat pumps locked in, the remaining variables for the COP equation will be the hot sink inlet and outlet temperatures ($T_{H,in}$ and $T_{H,out}$) representing the DH return and supply waters, respectively, and the cold source inlet and outlet temperatures ($T_{C,in}$ and $T_{C,out}$) representing the heat source temperature levels before and after entering the evaporator. The hot sink inlet and outlet temperatures in the modeling are obtained by the Equation (1) in 2.2. The currently utilized heat sources in European large-scale heat pumps are sewage water (900MW), ambient water (400MW), industrial waste heat (130MW), geothermal energy (100MW), flue gas (40MW) and district cooling (30MW) (David, et al., 2017). In addition to these, also ambient air as a heat source has been studied by the literature (Pieper, et al., 2019b); (Bach, 2014).

Sewage water is a stable heat source located close to the demand centers but is limited in its technical potential. Ambient water heat pumps are deployed e.g. in Sweden and Norway. However, these heat pumps require deep coastal sea areas, which are not found in Finland. Industrial waste heat is a good heat source in terms of the achievable COP due to its higher temperature level. However, it is also uncertain, as the industry may not exist for the full lifetime of the heat pump investment. Geothermal water in Finland requires relatively high investments in deep heat wells. Flue gas may only be used in parallel if some combustion technologies are used, and it is limited in its nature. District cooling may be used in larger cities with a cooling network. However, it does not provide significant potential, and least during the hours with the highest heat demand. (David, et al., 2017).

Hence, it can be summarized that many of the heat source alternatives are problematic to implement in Finland. The requirements for the heat sources studied in this thesis includes that it would be achievable anywhere in Finland. This excludes ambient water, industrial waste heat, flue gas, and district cooling from the analysis. Furthermore, the heat source should be utilizable in a wider scale. This excludes sewage water from the analysis. However, it is evident that if any low-cost local heat sources are available, they should be prioritized before the more expensive ones.

A heat source that fulfills the requirements set is geothermal heat. Geothermal heat provides a significant potential for heat production with a minimal environmental impact. The temperature of the directly achievable heat depends on the local geothermal gradient, meaning the temperature change per unit depth. (Frederiksen & Werner, 2013); (Tester, et al., 2015). A general geothermal gradient is at the order of 30°C/km. (Frederiksen & Werner, 2013). However, the geothermal gradient in Finland is somewhat lower than this value. According to two pilot projects located in Espoo, the geothermal gradient would be approximately 20°C/km in southern Finland (Helsingin Sanomat, 2019); (St1, 2020).

Therefore, if geothermal heat would be used directly for DH production in Finland, the well should be several kilometers deep to achieve the highest supply temperatures. One such pilot project by St1 is located in Espoo. The technology used in Espoo includes two 6.5km deep holes, which are connected by artificially stimulated wrecks in the bedrock. Coldwater is pumped down on the first hole, heated up in the wrecks acting as heat exchangers, and finally pumped up in high temperature to provide heat for the DH heat exchangers. (St1, 2020); (Tester, et al., 2015).

However, with the current technology, drilling such deep holes is very investment heavy and includes a high amount of risks related to e.g. the endurance of the drill in the depths. Even when the intended depth is reached, the thermal and hydraulic performance of the well may not equate the expectations. (Tester, et al., 2015). Also, stimulating the bedrock to generate wrecks may cause small-scale earthquakes even during the plant operation, which may lead to inability to operate the plant close to residential areas (Frederiksen & Werner, 2013).

The risks may be reduced by drilling shallower wells. The lower temperatures of these wells require a heat pump to be used in terms of achieving the DH supply temperatures (Frederiksen & Werner, 2013). A pilot project by QHeat in Espoo includes only one well instead of two. In this design, a coaxial pipe is used, in which water is pumped down in the outlines and brought up in the center of the pipe. In principle, the concept by QHeat resembles much of the technology used in regular small-scale local ground-source heat wells. However, where the small-scale ground source heat pumps utilize mainly stored solar energy from the shallow depths, the intermediate 2km wells utilize real geothermal heat. According to QHeat, the heat obtained from the 2km well equals to 35-40 small-scale ground source wells. (Helsingin Sanomat, 2019). Thus, an upside with the intermediate wells compared to the conventional shallow wells is that they can provide significantly more heat per land area, which is a clear advantage in dense urban districts (Frederiksen & Werner, 2013).

Hence, the first heat source to be studied in this thesis is intermediate deep, approximately 2km geothermal. The technology is still immature, and especially the costs of drilling the holes remain very high and uncertain. However, the drilling has historically been characterized by a steep learning curve (Tester, et al., 2015). According to QHeat, the estimated costs of the pilot project are approximately 1MEUR including one hole and a pump with its auxiliaries (Helsingin Sanomat, 2019). The estimate in this thesis is that the costs would drop to 400kEUR for one hole. Based on the estimations by QHeat, one hole would be enough to provide heat for a heat pump of approximately 0.3MW capacity and full load hours of 5500h. This means investment costs of 1330EUR/kW_{heat} for the geothermal well only.

A characteristic of geothermal heat is the waning of the amount of heat in the ground over time. To prevent the heat from running out over the lifetime of the geothermal plant or the heat pump, the use of the heat should be regulated and limited to a sustainable level. For this reason, the planned full load hours of the plant should be considered. To simplify the modeling process in this thesis, however, a fixed capacity based investment cost is used. An upside with the slow recharge of the well (and thus relatively low heat conductance in the ground), is that in case there is some available excess heat nearby, the well may also work as heat storage (Frederiksen & Werner, 2013).

The second heat source to be studied in the thesis is ambient air. Bach (2014) suggested that if seawater is not achievable as a heat source, outdoor air could be the second-best alternative. It fulfills well the requirement of availability anywhere in Finland, being also a well scalable alternative. The problems with air as a heat source include that it requires space, makes noise and is exposed for icing for some time of the year when the temperature is above zero and the humid air freezes in the evaporator. Also, the COP drops to its lowest during the times of the highest demand for DH. Due to the high variation in the heat source temperature, a seasonal performance profile should be used in the modeling. (Bach, 2014).

The hourly COP values of the chosen technologies are presented in Figure 10. The values are calculated according to Equation (7). The input values for the air-source heat pumps include the supply and return temperature of the DH water, as well as the outdoor air temperature. It has to be noted that as ammonia is chosen as the refrigerator, the maximum supply temperature of the heat pumps will be 90°C, which is the basis for the COP calculations as well.

When the required supply temperature exceeds this limit, other high-temperature technologies will be needed for priming the heat pump supply. The temperature of the air will drop 6°C in the evaporator, which is taken into account in the Equation (7). The input values for the geo-source heat pumps include the supply and return temperature of the DH water, and an estimated temperature of 22.5°C of the water temperature heated in the heat source and entering the evaporator. The estimation is based on the 2km well reference project in Espoo (Helsingin Sanomat, 2019). The temperature of the water will drop by 20°C in the evaporator.

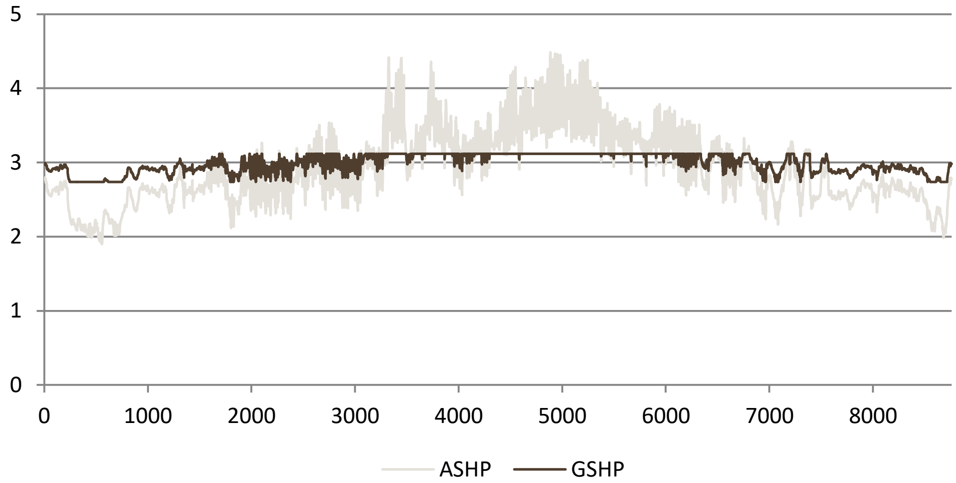

Figure 10. Hourly COP of air-to-water and geo-source heat pumps based on the temperature profile of Jyväskylä in 2014, DH supply temperature from equation (1), and equation (7).

The investment costs of heat pump installations in DH depend on the size of the installation, its configuration, components, and the heat source used. Pieper et al. (2018) divided these costs into cost fractions including the heat pump itself, the heat source, construction, grid connection, and consulting. Based on real reference projects in Denmark, the flue gas, sewage water, and excess heat heat pump projects were found to have the lowest total investment costs as the heat source related costs were lowest. The highest heat source related costs were found for groundwater heat pumps, the share being 35% of total costs of 690-770EUR/kW per produced heat. For air-source heat pumps the heat source related costs were found lower, but the grid connection and construction related costs higher. The higher grid and construction related costs may be explained by the lower COP and thus higher electricity consumption and building costs related to e.g. the fans. The total investment costs for large (4-10MW) air-source heat pump projects were reported at 700-730EUR/kW_{heat}. (Pieper, et al., 2018).

The groundwater heat source in the study comprises only shallow wells below 300 meters, and thus the investment costs for the heat source differed much from the analysis in this thesis presented above. As the access for groundwater in wider scale heat pump utilization may be cumbersome, these investment costs are not used in the modeling of this thesis. Instead, the result from the analysis above, 1330EUR/kW_{heat}, for the heat source is used. Estimating the other project related costs from Pieper et al. (2018), the total investment costs for geo-source heat pumps will then add up to 1800EUR/kW_{heat}. For the air-source heat pumps the result from Pieper et al. (2018), 700EUR/kW_{heat}, is used in the modeling.

The heat pump investments are most profitable when the operating hours are high. This is how most of the existing heat pumps are designed to operate in the DH systems, some heat pumps even reaching as high operating hours as 7000-8000h. However, the new installations would potentially also take advantage of the volatile electricity prices caused by increasing amounts of intermittent renewable production. (Dahl, et al., 2019).

Also, heat pumps may even be used for demand response by reducing their electrical power demand, if local heat storage is available (Frederiksen & Werner, 2013). In this kind of operation, the current installations are exposed to increased mechanical wear, mostly related to the compressor. However, it may also be a matter of design, as the existing heat pumps are simply not designed for such operation. (Dahl, et al., 2019).

2.3.2.2 Electric Boilers

An electric boiler is a simple device where water is heated up by a current passing through it. The current is controlled by changing the active surface area of electrodes inside the water tank. The thermal efficiency of electric boilers is close to 1, depending on the boiler insulation. (Frederiksen & Werner, 2013). In 2018, the DH production with electric boilers in Finland was around 100GWh, accounting for approximately 0.3% of all DH production (Finnish Energy, 2019).

As other heat only boilers, the electric boilers in DH are thermodynamically not very ideal, as high-quality electrical energy is used to produce low exergy heat. However, compared to heat pumps that produce more heat with lesser electricity, the electric boilers have significantly lower investment costs and less ramping constraints, which make them more suitable for grid ancillary services. (Nielsen, et al., 2016). The value of this kind of operation will most likely increase alongside the increasing amounts of variable renewables in the electricity system (Frederiksen & Werner, 2013). More renewables may also lead to more hours with low electricity prices leading to potentially low-cost heat production with electric boilers. However, efficient utilization of these low price hours may require heat storage capacity in the system. (Nielsen, et al., 2016).

2.3.2.3 Thermal Energy Storages

Though Thermal Energy Storage (TES) is not a technology for heat production, it is highly complementary to a variety of production technologies. Furthermore, TES provides valuable flexibility to be utilized in handling the demand variability and market variations. In principle, TES enables balancing the supply and demand in a way that minimizes the marginal cost of heat produced in the system as a whole (Thomsen & Overbye, 2015).

TES may be divided into three categories according to their technical characteristics, which are Sensible Heat Storages (SHS), Latent Heat Storages (LHS) and Thermochemical Energy Storages (TCES). The principle of sensible heat storages is to increase the temperature of a storage medium by adding heat to the storage, and vice versa. The heat capacity of SHS depends on the volume of the storage as well as the specific heat of the storage medium. Water is a usual storage medium due to its high specific heat value. To avoid boiling, the water has to be kept below 100°C in non-pressurized storages. Pressurized storages enable higher temperatures and hence higher energy densities for the storage. (Khartchenko & Kharchenko, 2014). However, the investment costs for pressurized storages are also higher (Frederiksen & Werner, 2013).

LHS enables even higher energy densities than pressurized sensible heat storages. The heat storage in such storage is based on the reversible phase change (usually melting) of a phase change material, where absorption and release of latent heat occur in charge and discharge operation, respectively. The storage medium in LHS is usually salts or salt mixtures. In addition to the higher energy densities, LHS also enables storing heat in much higher temperatures, even several hundred degrees Celsius. This allows e.g. electricity production with a steam turbine with the output heat. Lastly, the TCES is based on reversible chemical reactions. (Khartchenko & Kharchenko, 2014).

Only sensible heat storages are considered in this study, as the investment costs for latent heat and thermochemical energy storage are considerably higher than the ones of sensible heat storages. Sensible heat storages are a good fit for DH systems, as the required output temperature levels are relatively low. (Thomsen & Overbye, 2015). Furthermore, it is assumed that the storage is at atmospheric pressure, as this allows larger storage sizes with lesser investment costs. The heat output of this kind of storage only requires priming during the few hours in a year when the supply temperature exceeds the boiling temperature of the medium (Thomsen & Overbye, 2015). Hence, the maximum output temperature of the heat storage is a bit less than 100°C. In this thesis, discharge temperature of 90°C is used.

In the sensible heat storages used in DH, cold water is located at the bottom of the storage, whereas hot water is located at the top. Thus, the bottom is connected to the DH return water, whereas the top is connected to the supply side. (Thomsen & Overbye, 2015). The connection may be implemented by directly by using DH water in the storage or indirectly by connecting the storage to DH by heat exchangers (Frederiksen & Werner, 2013). The former one requires the pressure level to be the same as in the network, meaning pressurized storage in the conventional Finnish DH networks. The latter is a viable way to connect non-pressurized storage. Non-pressurized storages may also be connected without heat exchangers, as long as the pressure levels are separated, e.g. by utilizing pumps and valves. (Thomsen & Overbye, 2015). An illustration of a simple sensible heat storage utilized in DH is presented in Figure 11.

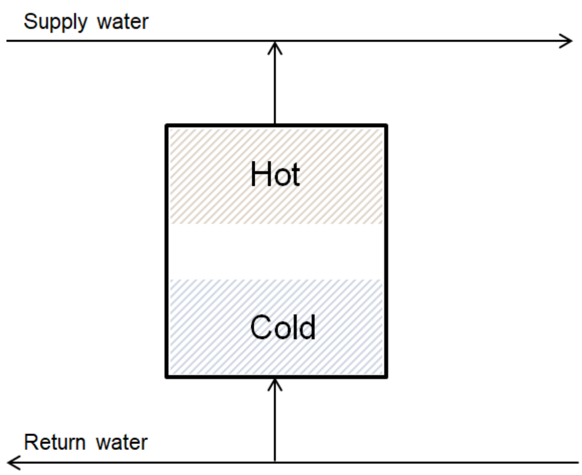

Figure 11. Simple sensible heat storage used in DH.

According to the role of the storage in the DH system, the storages may be divided into inter-seasonal and short term storage. The purpose of inter-seasonal heat storages is to shift the load inter-seasonally to better match the production pattern, e.g. from high loads in winter to the lower loads in summer. These kinds of storages are however still in their development phase and include high investment costs due to their large size. (Frederiksen & Werner, 2013); (Thomsen & Overbye, 2015).

Instead, short term storages are already somewhat utilized in the DH systems. The main purpose of short term storages is to shift the load from the peak load hours to the hours with lower demand (Thomsen & Overbye, 2015). Thus, this shifting of load may also be called “peak-shaving”. In this way, the short term storages enable higher utilization of base load heat production during the low demand hours and replace the costly peak load production by discharging this heat during the peak load hours. The amount of peak load production that can be replaced depends on the size of the storage. (Frederiksen & Werner, 2013); (Thomsen & Overbye, 2015). However, it has to be noted that storage does not add capacity to the system, and hence it does not decrease the need for peak load capacity which also functions as a part of reserve capacity in the system (Thomsen & Overbye, 2015).

In addition to peak shaving, heat storage may also be utilized in integrating the heating and power markets (Dahl, et al., 2019). For example, the variation in electricity price may be utilized by prioritizing CHP production during the hours of high and power-to-heat technologies during low electricity prices. Considering only the complementary benefits for CHP production, the optimal control strategies vary a bit between the back-pressure and extraction-condensing plants.

For back-pressure plants the storage enables an unattached operation from heat demand, optimizing the production only according to the electricity prices. On the other hand, extraction-condensing plants can utilize heat storages by discarding the heat production completely during the high electricity prices, provided that the storage level is sufficient to satisfy the remaining heat demand. On the contrary to back-pressure plants with auxiliary cooler, the extraction-condensing plants are able to increase the electricity production efficiency somewhat compared to operation at back-pressure mode. (Thomsen & Overbye, 2015). Furthermore, heat storages enable power-to-heat technologies to provide valuable auxiliary services for the electricity system (Frederiksen & Werner, 2013). Heat storages in DH systems have been studied e.g. by (Hast, et al., 2017), (Valor Partners, 2016), (Nielsen, et al., 2016).

A similar kind of benefits for the DH system may also be achieved by demand response. Here, the thermal inertia of the customers is utilized, so that they would shift their consumption from the peak demand hours to the previous or preceding hours. The shift potential is usually some hours and does hence only work for shaving short-term peaks in the demand. (Frederiksen & Werner, 2013). Demand response in DH has been studied e.g. by (Valor Partners, 2015) and (Pöyry Management Consulting, 2016). As the required investment costs for demand response is hard to predict, and the maximum peak-shifting potential is relatively limited, only heat storages are included in the modeling of this study.

The investment costs for heat storages vary a lot depending on the type of storage and its size (Thomsen & Overbye, 2015). Furthermore, it is much cheaper to build large heat storage, if existing and suitable infrastructure already exists. Such was the case for Helen and Vaasan Sähkö, which both are building large heat storages in caves that have previously been used as oil storages (Tekniikka & Talous, 2018), (Vaasan Sähkö, 2019). If the storage has to be built up from scratch, the investment cost per storage capacity will be much higher. This was the case for example for Etelä-Savon Energia, who built new steel cylinder heat storage (Motiva, 2019). The technical and cost data of these reference storages are represented in Table 2 below.

Owner	Helen	Vaasan Sähkö	Etelä-Savon Energia
Storage type	Atmospheric pressure sensible heat storage (converted oil cave)	Atmospheric pressure sensible heat storage (converted oil cave)	Atmospheric pressure sensible heat storage (steel cylinder)
Year of commissioning	2021	2020	2016
Capacity (m^3)	260 000	210 000	7 000
Capacity (MWh)	11 600	7 000 – 9 000	350
Investment (kEUR)	15 000 (estimate)	5 000 (estimate)	2 500 (actualized)
EUR/m^3	57.8	23.8	357.1

Table 2.Estimated and actualized investment costs of heat storage and their technical data. Source: (Tekniikka & Talous, 2018), (Vaasan Sähkö, 2019), (Motiva, 2019).

Various literature estimates on heat storage costs have also been made. Hast et al. (2017) estimated that the costs of heat storages would increase linearly with a variable term of 33EUR/m^3 and a fixed term cost of 400 000EUR. The real estimate on the Helen storage would be a bit higher than according to the approximation, Vaasan Sähkö storage slightly below the approximation and the Etelä-Savon Energia storage realized costs somewhat higher than according to the approximation.

Valor Partners (2016) used only a variable cost of 100EUR/m^3 for the storage investment costs. This would lead to the result of the same direction as the estimate by (Hast, et al., 2017), but is further away from the real cost estimates for the storage investments. Another estimate by Dahl et al. (2019) was 210EUR/m^3 for storage tanks and 35EUR/m^3 for storage pits. The estimate for the storage tanks matches quite well with the Etelä-Savon Energia storage, whereas the estimate for the pit storage stays in the range of the Helen and Vaasan Sähkö cave storages. The comparison of the investment estimates and costs used in the literature are presented in Figure 12.

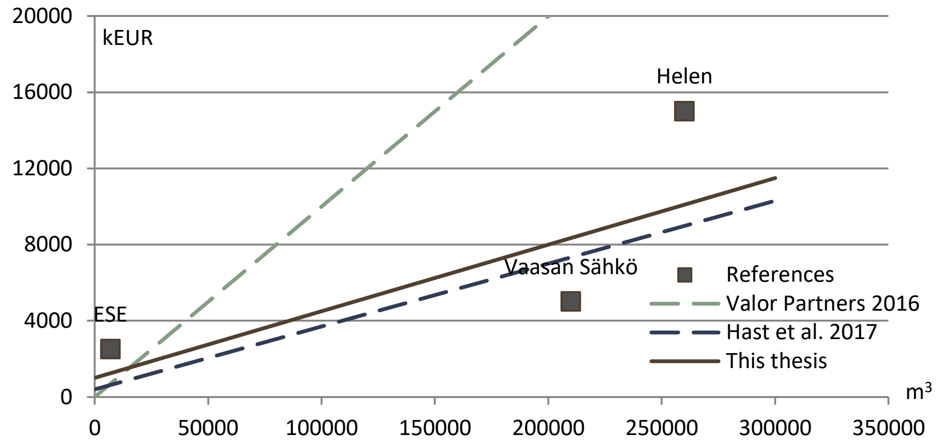

Figure 12. Comparison of heat storage investment costs used by literature and estimates/actualized costs of real heat storage projects. Sources: (Hast, et al., 2017), (Valor Partners, 2016), (Tekniikka & Talous, 2018), (Vaasan Sähkö, 2019), (Motiva, 2019).

All in all, the literature estimates somewhat underestimates the investment costs for small heat storage, and especially the ones of projects that are not able to utilize existing infrastructure, such as oil caves. On the other hand, the large heat storages are here somewhat overestimated. Here again, the investment costs of these reference projects are lower due to the utilization of existing infrastructure. If no utilizable infrastructure exists at the site, the investment cost will most likely be higher than the ones of these reference projects. As a compromise, a fixed term of 1 000EUR and a variable term of 35EUR/m^3 are used in this thesis.

The energy content of one cubic meter of storage depends on the return water temperature in the network, and the maximum temperature of the storage. As mentioned before, a storage maximum temperature of 90°C is used in this thesis, whereas the return water temperature is 45°C. The energy content per cubic meter of storage can be calculated as:

$$Q = c\rho\Delta T \tag{7}$$

where

c the specific heat of water, 4.2 kJ/kg°C
ρ the density of water, 1000kg/m^3

$$Q = 4.2\frac{kJ}{kg°\text{C}} \times 1000\frac{kg}{m^3} \times (90°\text{C} - 45°\text{C}) = 189\,000\frac{kJ}{m^3} = 0.0525\frac{MWh}{m^3}$$

This value is used in the calculations of this study.

2.3.2.4 Other non-combustion technologies

Other possible non-combustion technologies for DH production could be solar heat collectors and small scale nuclear reactors (Frederiksen & Werner, 2013). Solar heat collectors have been studied by (Hast, et al., 2017) and were not found economically feasible for the studied network. The problem with solar heat collectors is that the production is very variable. With smaller heat storages it is possible to even out the shorter term, such as diurnal variations in production. However, smoothing out the inter-seasonal variations in production would require much larger storages leading to heavy investments. (Frederiksen & Werner, 2013); (Thomsen & Overbye, 2015). With the long winters in Finland with less available solar radiation and high heat demand, this kind of storage would be unprofitable. Thus, the plants could only serve during the summertime, when the consumption is at its lowest. Therefore, solar heat would only provide savings in other energy consumption, but would not replace any capacity in the system.

Modular nuclear reactors for DH production in the Helsinki region have been studied by (Värri & Syri, 2019). The technology would provide a CO_2 free alternative to replace existing fossil fuel base load CHP plants. The results of the study indicate that both HOB and CHP alternatives of nuclear heat production could be profitable, though the profitability of the CHP plant heavily relies on future electricity prices. (Värri & Syri, 2019). However, the deployment of the technology in the near future includes a lot of uncertainties related to e.g. the costs and acceptability. For the aforementioned reasons, further analysis of both solar heat collectors and modular nuclear reactors are excluded from the scope of this study.

3 District Heating Development Paths

Ambitious renewable targets from both the EU and the Finnish Government have triggered wide transitions in the Finnish DH systems. Practical examples of such targets are the recent coal ban and intentions to halve the usage of peat in heat and power production by 2030 (Finnish Government, 2019). To address these changes, a development path in which an increased amount of biomass would be used for DH production could be considered possible. Another way to address the situation could be a wider scale electrification of DH and thus couple the heat and electricity sectors.

3.1 Increased Biomass Use and Biomass Resource Efficiency

The total Finnish bioenergy usage in 2018 was 114TWh, consisting mainly of forest biomass (Statistics Finland, 2019). The forest biomass for energy use can be divided into forest chips which are wood directly collected for energy production and forest industry by-products. The forest chips feedstocks include e.g. stem wood, primary forest residues such as logging residues, stumps and minor amounts of industrial-sized timber that is directly used in energy production (e.g. logistical or quality-related reasons). The by-products include e.g. bark, sawdust, industrial chips, black liquor, and other concentrated liquors. (Bioenergia ry, 2019); (European Commission, 2017). The liquors from the forest industry are almost fully used by the industry themselves for their energy production (Luke, 2019).

The forest biomass used in DH production mainly consists of solid forest biomass. The total consumption of solid forest biomass in heating and power plants (including DH production as well as other industries) was in total 38.4TWh in 2018. Of this, 57% was originated from forest industry by-products, comprising mainly bark and sawdust. The forest chips accounted for 37% of the solid wood fuel usage during the same year. The rest included recycled wood and wood pellets and briquettes. (Luke, 2019). A Sankey diagram of the bioenergy use in Finland and solid forest biomass consumption in heating and power plants is presented in Figure 13.

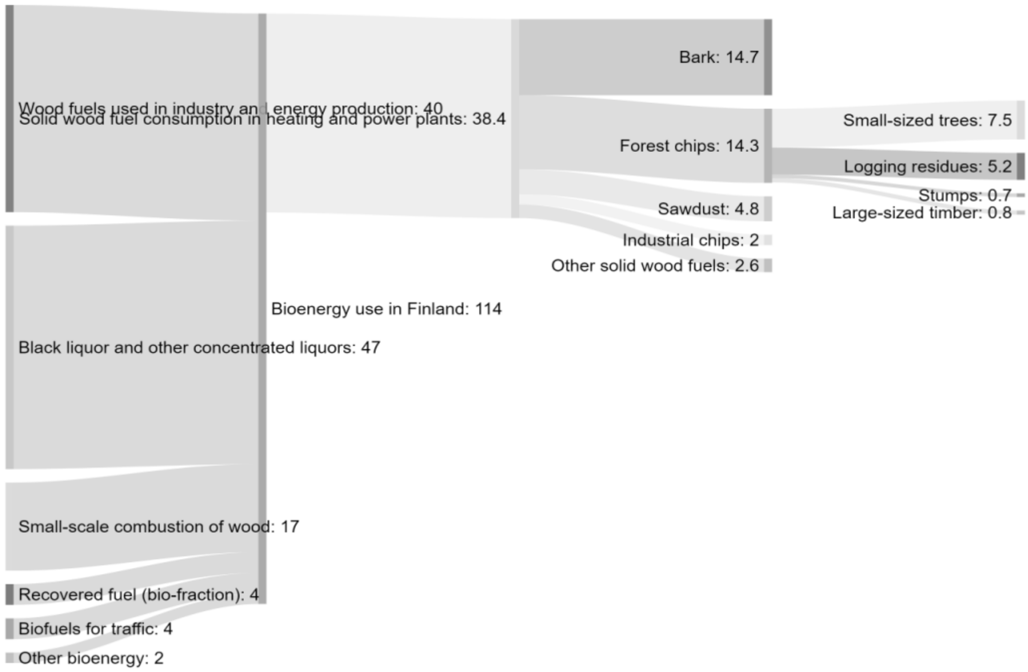

Figure 13. Bioenergy use in Finland and solid wood fuel consumption in heating and power plants in 2018 (TWh). Data sources: (Statistics Finland, 2019), (Luke, 2019). Diagram rendered with SankeyMatic.

The largest share of forest biomass for energy production originates from side streams of the forest industry. These side streams include forest industry by-products and logging residues. Hence, the availability of forest biomass largely depends on the amount of commercial loggings. Of these loggings, the timber offcut, refinement residues and wood not valid for refinement may be utilized for energy production. The supply of biomass fractions originated from the side streams is currently somewhat increasing due to new investments in the forest industry. (Finlex, 2018); (Heinonen, et al., 2017). The development of commercial loggings is presented in Figure 14.

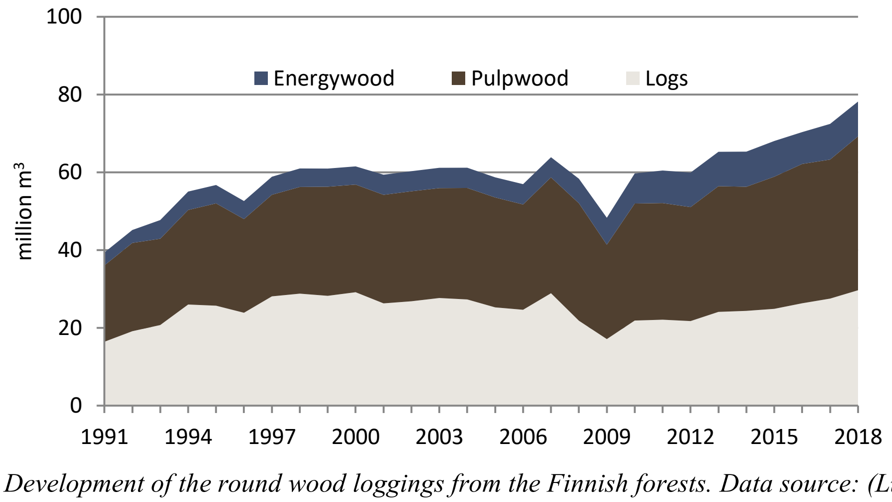

Figure 14. Development of the round wood loggings from the Finnish forests. Data source: (Luke, 2019)

However, the increase in the supply from forest industry side streams will be limited and it may not even be sustainable to increase the loggings much further. According to Heinonen et al. (2017), the maximum sustainable annual round wood harvest level for a longer period (multiple decades) would be $73Mm^3$ (Heinonen, et al., 2017). In 2018, the total round wood loggings were already above this at the level of $78.2Mm^3$ (Luke, 2019). As the potential of the current side streams is already largely utilized due to efficient use of by-products, the main potential for further supply growth of domestic forest biomass lies in the forest chips (including also the logging residues which can be collected more broadly with some effort) (Kallio, et al., 2015). As the forest chips as a resource are more distributed than the by-products, the logistics becomes more of an issue (Pöyry Management Consulting, 2019).

In DH, forest chips already represent the major part of forest biomass usage. The total forest biomass use in DH was 15.8TWh in 2018. Of this, forest chips accounted for 64% and by-products for 36%. The rest of the by-products are used mainly for the forest industry's energy production. (Finnish Energy, 2019). The share of DH in the total forest chips use for energy production was 71% in 2018 (Luke, 2019).

The largest sustainable potential supply of forest chips in Finland during the period of 2015-2024 is estimated at $23.3Mm^3$ ($15.4Mm^3$ without stumps). From 2025 to 2034 the same potential is estimated at $27.4Mm^3$ ($20.4Mm^3$ without stumps), and in 2035-2045 $27.6Mm^3$ ($20.5Mm^3$ without stumps). (Luke, 2019). Recently, the use of stumps for energy production has remained low and even decreased during the 2010s. The development may be explained with environmental, technical and economic causes. The Ministry of Agriculture and Forestry in Finland suggests that stumps that are below 15cm in diameter, and that a considerable amount of larger stumps should be left to the ground for environmental and soil productivity reasons. Furthermore, stumps are more costly to harvest and chip than other forest biomass, and the use of stumps may also be technically challenging due to impurities in the fuel. (Tapio, 2019).

A spatial presentation of the sustainably available forest chips potential in Finland including and excluding stumps is presented in Figure 15. The forest chips potential is highest at the central and eastern parts of Finland and lowest in the northern parts and coastal areas.

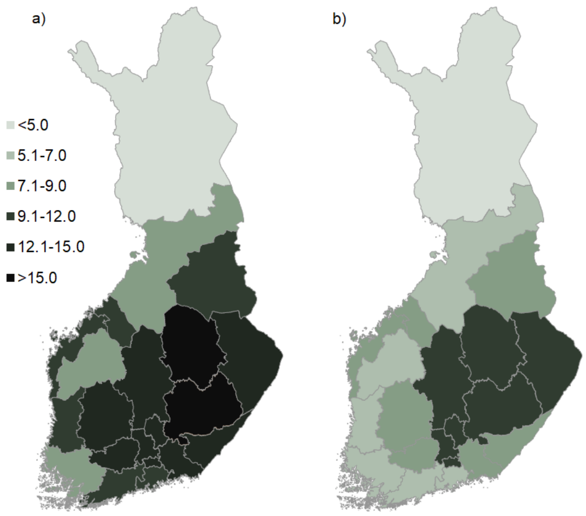

Figure 15. Estimated sustainably available forest chips potential in Finland during 2025-2034 as thousand m^3/ha/year, a) total amount of forest chips and b) excluding stumps. Data source: (Luke, 2019).

The available potential may be compared to the current fuel usage in heat and power production in Finland, which is the sector with the largest demand for forest chips. The total fuel usage in Finnish heat and power production in 2017 was 143TWh. The fossil fuel usage (including peat) amounted to 55TWh. (Statistics Finland, 2017). Following the coal ban in 2029 (Finlex, 2019), the 19TWh of coal usage will be ceased and at least for the most part replaced with another fuel. If the halving of peat usage by 2030 planned by the Finnish Government, another 7TWh will be replaced. According to the government, also the rest of the peat usage will cease market-based during the 2030s, after which peat would remain only as a security of supply fuel. (Finnish Government, 2019). This would lead to another 7TWh of fuel to be replaced. The ban of oil together with coal may be considered rather likely, adding another 4TWh of fuel to be replaced. In total this would mean 30TWh of fuel to be replaced by 2030 and 37TWh by 2040.

Furthermore, also the use of other fossil fuels (natural gas and oil) is possible to cease market-based in the future due to increases in emission allowance prices and taxes. In DH, these fuels represent mostly peak load production (Frederiksen & Werner, 2013). The replacement could take place e.g. by utilizing low-cost boiler technologies with renewable fuels, or by utilizing heat storages to reduce the need for peak load production in the first hand (Thomsen & Overbye, 2015). However, it has to be taken into account that if the amount of CHP production in DH is to drop and the electricity production of the units to be replaced by nuclear and wind production and by imports, the total fuel usage in heat and power production will decrease somewhat. Also, further energy efficiency measures may decrease the primary energy use in the future (Frederiksen & Werner, 2013). The fuel usage in heat and power production in Finland in 2017 is presented in Figure 16.

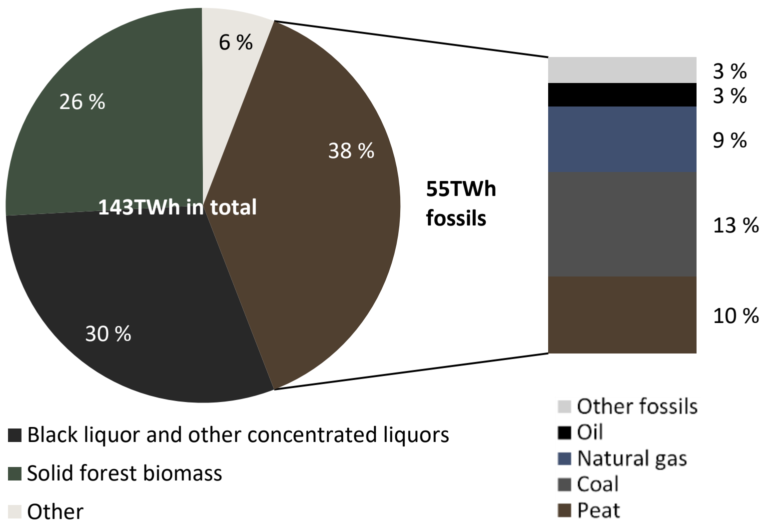

Figure 16. Total fuel usage in heat and power production in Finland in 2017. Data source: (Statistics Finland, 2017)

DH production (CHP and HOB) accounted for approximately 37% of the total fuel usage in heat and power production (Finnish Energy, 2019). In DH, the share of fossil fuels is much higher than in heat and power production for industrial usage (Statistics Finland, 2017). This is mostly because of the large forestry industry in Finland, which uses a significant amount of forest biomass by-products for their energy production (mostly black liquor used by pulp industry) (Luke, 2019). Therefore, DH will provide the main potential for further forest biomass demand. As mentioned before, the increasing demand would have to be mostly covered by forest chips, as the by-products are already largely utilized.

The spatial distribution of total fuel usage and forest biomass usage in DH production in 2018 is presented in Figure 17. The figure shows that the fuel usage is currently clearly focused on south-west Finland, and especially to the capital area. Also, the forest biomass usage is as highest in southern Finland. However, especially in the capital area, the total fuel usage is on a whole different level than in other areas, whereas the forest biomass use is only somewhat higher. Hence, there is considerable pressure for a further increase in forest biomass use in the capital area. Thus, considering that the estimated sustainable forest chips supply potential is relatively low in south-west Finland, also the deficit areas for forest chips would most likely be located in south-west Finland.

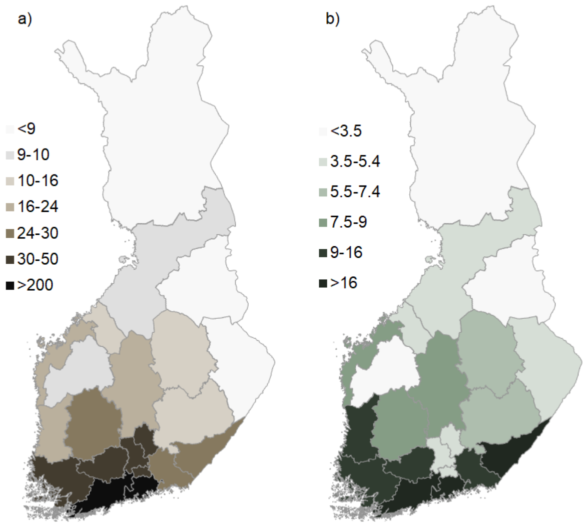

Figure 17. Fuel usage in DH production in Finland in 2018 as GWh/h, a) total fuel usage and b) forest biomass usage. Data source: (Finnish Energy, 2019).

An increased resource scarcity of forest chips in certain areas in Finland is possible. If the forest chips potential is converted into energy using a conversion factor of $1Mm^3$=2TWh, the total potential for forest chips supply during 2025-2034 excluding stumps would be 40.8TWh. Of this potential, 14.3TWh is already utilized, leaving a potential for a further increase of 26.5TWh. Compared to the discussed fuels to be replaced in the future (30TWh by 2030 and 37TWh by 2040), it seems that forest chips potential excluding stumps would not be fully sufficient to replace the current use of the fossil fuels to be replaced even at the country level. However, this comparison neglects e.g. the impact of potentially decreasing amounts of CHP, energy efficiency measures, and the moderately increasing amount of forest industry by-products, which all positively affect the supply-demand balance for forest chips in the future. In any case, though on the country level the supply would almost satisfy the demand, collecting forest chips afar from demand would become expensive.

If biomass is to be imported by ships to Finland, it would most likely be originated from Europe. Importing may come into question to the coastal deficit areas, as also the domestic logistics of forest biomass over longer distances by trucks is expensive (Pöyry Management Consulting, 2019). The availability of forest biomass in Europe has been studied in various studies, e.g. (Verkerk, et al., 2011), (Mola-Yudego, et al., 2017), (European Commission, 2017), (Verkerk, et al., 2019). The theoretical total yearly forest biomass potential in Europe from 2010 to 2030 is estimated to be rather stable, around 1250Mm^3 (Verkerk, et al., 2011); (European Commission, 2017). However, various environmental, social and technical constraints reduce the amount of biomass that can be harvested from the forest. This would be around 744Mm^3 in 2010 and between 623 and 895 Mm^3 (Verkerk, et al., 2011) or 710Mm^3 (European Commission, 2017) in 2030.

The constraints with the largest impact on forest biomass availability in Europe are a large amount of small-sized forest holdings and the environmental considerations related to soil productivity (Verkerk, et al., 2011). The scattered ownership base of the forest causes a structural challenge for wide-scale resource utilization, whereas the environmental consideration and the acceptability of forest biomass as a resource lead to significant uncertainty for the utilizable potential. The largest sustainable biomass potential can be found in northern and central Europe. However, much of this potential is already utilized. (Verkerk, et al., 2019). When considering the unused potential, northern Europe and Finland do no more stand out significantly from other parts of Europe. The spatial distribution of the potential sustainable forest biomass availability is presented in Figure 18.

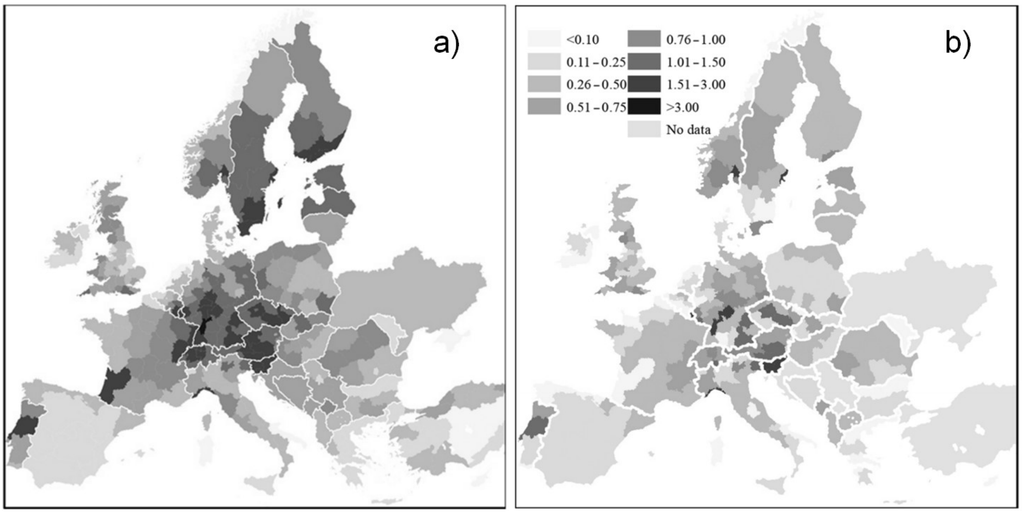

Figure 18. The spatial distribution of the potential sustainable forest biomass availability in Europe per unit of land (t/ha/year). a) represents the total available forest biomass and b) the unused potential. Modified from (Verkerk, et al., 2019).

The realizable yearly potential of forest biomass for heat and power production in Europe would be 357Mm^3 in 2010, and between 109 to 380 Mm^3 in 2030. This excludes the forest biomass needed for material use (including the internal forest biomass energy use within the forest industry). Also in Europe, the availability of forest biomass for energy production is highly dependent on the projected amount of the future material use of wood resources, as these use cases both produce by-products for energy use and may also compete of the resource. (Verkerk, et al., 2011). The available potential for forest biomass for energy production from forest chips (excluding forest industry by-products) in Europe would be 160Mm^3/a (Mola-Yudego, et al., 2017). Whether the stumps are used or not has a significant effect on the realizable resources on both of the estimates. Furthermore, the economic constraints related to transportation distances and networks may further decrease the potential (Verkerk, et al., 2019).

According to Kallio et al. (2015), the required amount of yearly wood-based heat and power production in Europe to achieve the 2°C target set in the Paris Agreement in 2015 would be 214Mm^3 in 2040. (Kallio, et al., 2015). In comparison, the amount of wood used in energy production in Europe in 2010 was approximately 75Mm^3 (Kallio, et al., 2018). Therefore, there would be an increase of 140Mm^3 in forest biomass demand for heat and power production if the 2°C target should be achieved. Depending on the level of mobilization of forest biomass in 2030-2040, a demand of 214Mm^3 could potentially be covered by the estimated potential (109-380Mm^3) (Verkerk, et al., 2011). However, there are clear risks for resource insufficiency even at the European level.

A competing use case for forest biomass used in heat and power production in Europe is biofuels. Kallio et al. (2018) studied how the alternative combinations of biofuel and biomass prices affect the allocation of wood biomass between biofuels and heat and power production in Europe. Depending on the assumed price of the liquid biofuel output that the producers would achieve in different scenarios, the heat and power producers should be able to pay 25-44 EUR/MWh of the energy wood in 2040, if the 2°C goal including 214Mm^3 wood-based heat and power production (Kallio, et al., 2015) should be achieved. According to the study, the policy choices will have a strong impact on the allocation of biomass use between the production of liquid biofuels and heat and power production. Due to the uncertainty regarding the policies and future price developments on biomass resources and biofuel prices, the uncertainty of the investments in biofuel production capacity is large. (Kallio, et al., 2018).

A similar kind of study for the Nordic region was conducted by Mustapha et al. (2019). According to the study, the forest biomass usage for heat and power generation will likely compete with increasing demand for forest-based liquid biofuels in the Nordics. The competition of the same resources will most likely increase the biomass price for energy production use and decrease biomass HOB and CHP competitiveness compared to other heat production technologies. (Mustapha, et al., 2019). A practical example of this kind of development in the Nordic area is the planned biorefinery to Kemi, Finland, which would use forest biomass as its primary feedstock. The yearly demand for forest biomass for the plant would be approximately 2.8Mm^3. (Kaidi Finland, 2019).

In addition to biofuels, other use cases may compete of the forest biomass resources with energy production. The alternative use cases often also provide more economic value and have a more positive effect on the carbon balance than combusting the biomass (Seppälä, et al., 2019). The new growth rate together with the stored time of carbon in the biomass use case builds up the effect of the harvesting of the biomass on the carbon balance (The Finnish Climate Change Panel, 2015). In addition to the effect on the carbon balance of the harvesting itself, one has to take into account the carbon emissions caused by the alternative products that would have been used without the biomass use case (Seppälä, et al., 2019).

To compare the carbon balance influence of using biomass-based products instead of non-biomass based subsidiary products between different use cases, displacement factors may be used. The displacement factor expresses the amount of reduced CO_2 emissions per mass unit of wood used when producing a functionally equivalent product or fuel. On the other hand, the required displacement factor expresses the required amount of reduced CO_2 emission per mass unit of wood used to rationalize the harvesting level in terms of carbon balance. According to Seppälä et al. (2019), the required displacement factor in Finland in the long term considering the projected increases in the harvest levels would be roughly double to the average displacement factor of the currently manufactured Finnish wood-based products and fuels. (Seppälä, et al., 2019)

The carbon neutrality of biomass in energy production is based on the principle that the carbon debt originated from harvesting the biomass from the forest is recovered due to the carbon bound by the new growth in the area. The time taken to bind the same amount of carbon as included in the harvested biomass depends on the type of forest and its new growth rate. (The Finnish Climate Change Panel, 2015). Often this means several decades, which can be seen problematic as immediate actions should be taken in tackling climate change (IPCC, 2019).

Usually, the immediate emissions are even higher than the ones of the fossil fuel alternatives. Instead, construction of buildings out of wood would replace e.g. steel and the emissions caused by producing the steel. Furthermore, the carbon will be bound to the building for decades to go. Together with the carbon that is slowly bound by the new growth, this means that the carbon balance will look very good for a longer period, and have immediate positive effects. (Seppälä, et al., 2019); (The Finnish Climate Change Panel, 2015). Of course, the forest biomass used in energy production is much lower in its quality than the round wood used for construction.

A practical example of lower quality biomass utilization for more valuable use cases than combusting is Fortum's Bio2X project. The core of the project is the fractionation technologies that can be used to separate the biomass (including forest biomass) into lignin, cellulose, and hemicellulose, which can then further be used to replace fossil-derived raw materials in industrial and consumer sectors (e.g. textile fibers). Also, bioethanol and biochemical production come before straight conversion into end-use energy in the project. (Fortum, 2019). Similar kind of research has been done by Metsä Board in their Äänekoski bioproduct plant commissioned in 2017 (Metsä Board, 2019).

Forest biomass may also be used in high-temperature industrial purposes. From the thermodynamic perspective, this would make much sense, as the high exergy content of the fuel would be utilized more than in DH production if electricity is not produced (Sipilä, 2015). Finding renewable alternatives other than biomass for the high-temperature processes is much more challenging than for DH (Taibi, et al., 2012). Biomass use is already generalized in the forest industry. However, the use could be extended to other industries as well, e.g. the metal industry. Currently, there are barriers such as high investment costs of biomass systems and the competition with low-cost fossil fuels. Therefore, some kind of political action may be needed to incorporate biomass use in industries with no own biomass resources. The challenge is that unlike heat, commodities such as steel may as well be produced elsewhere if e.g. carbon is to be taxed in a certain area. (Malico, et al., 2019).

Figure 19 represents the concepts of cascading-in-time and cascading-in-value, which can be utilized in the biomass framework. Cascading-in-time means that the resource should be re-used sequentially in the order of the specific resource quality at each stage. Once it is not fit for this purpose anymore, it will be handed out to the next use case. In this way, the carbon in the biomass will also ideally be bound into the products for a longer period. Cascading-in-value means that the biomass resource is always used for the use-case having the best economical and/or environmental contribution. Only the residual or parts that are not fit for any other purpose will be used as fuels and energy. The two concepts should be used in parallel to achieve the best economical and/or environmental outcome of the resource utilization. (IEA, 2016).

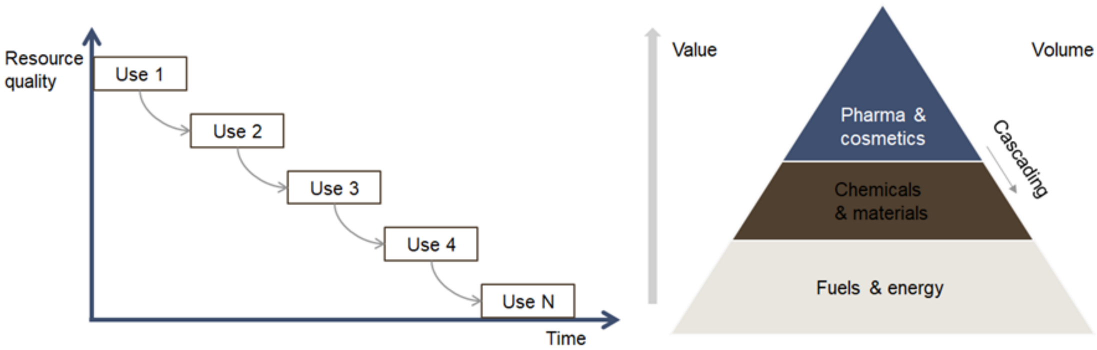

Figure 19: The "cascading-in-time" and "cascading-in-value" concepts. Modified from: (IEA, 2016)

The historical prices of forest biomass in Finland have remained relatively low with little upward pressure. The price level of forest chips for heat production plants has since 2013 been slightly above 20€/MWh. The price increase of exported fossil fuels since 2016 has improved the competitiveness of forest chips (and peat) recently. (Statistics Finland, 2019). The increase in the prices of fossil fuels is partly due to an increase in the excise tax, of which biomass is fully and peat almost fully exempted. The difference in the fuel prices for CHP and heat only production plants is also due to tax exemptions. In principle, the fuels used for electricity production in Finland are exempted from tax, whereas fuels used for heat production includes excise tax. The fuels used in CHP production have their own lowered tax calculated considering the fore mentioned principle. (Tax administration, 2019). The price development of wood chips and other fuels for heat production units is presented in Figure 20.

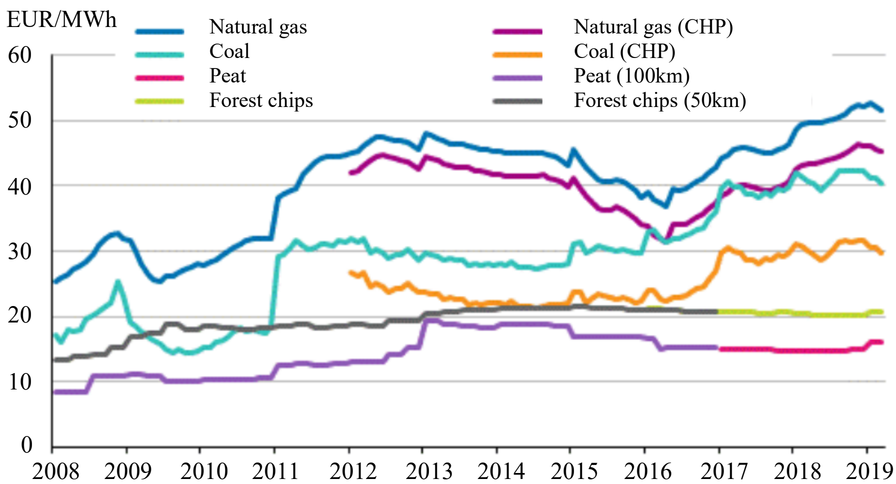

Figure 20. The price development of fuels used in heat production units. The prices include excise tax (VAT 0%). Modified from: (Statistics Finland, 2019).

In the future, the forest biomass price for energy production may increase due to its increased demand for energy production and the competition of the resource between different use cases. In this thesis, a forest chips price increase of 15% from the price level of the end of 2019 is expected for the year 2030. This would mean a price increase from the current level, 21.0 to 24.2EUR/MWh. The same kind of price increase is assumed for wood pellets, meaning a price increase from 33.0EUR/MWh to 38.0EUR/MWh. As the forest chips price in 2030 is very hard to predict, sensitivity analysis is also done with a price increase of 0% (low scenario) and a price increase of 30% (high scenario), which would mean prices of 27.3 and 42.9EUR/MWh for forest chips and wood pellets, respectively.

The estimated price levels may be considered conservative when compared to the estimates for wood energy prices in Europe made by (Kallio, et al., 2015). Another literature estimate for wood chips prices in Finland was 32EUR/MWh and 40EUR/MWh in 2030 and 2050, respectively (Hast, et al., 2018b). However, the forest chips price in Finland will most likely not reach the average European price due to the higher than average local supply and relatively expensive logistics. Sensitivity analysis will also address the fact that forest chips price may vary according to the location of the DH network along with the variation in forest chips supply.

Another dimension to consider related to the increasing use of biomass is the national security of supply in energy. One characteristic of biomass as a fuel compared to the conventional fossil ones is the poor storage capabilities due to a lower energy density and the fast spoilage of the fuel without more advanced storage facilities. Thus, reliable and continuous logistical chains would be required. The low energy-density means also less efficient and more expensive logistics. Furthermore, the increasing amounts of imported biomass arise security of supply risk if ever there are disturbances in the import. In case of an import disturbance, there has to be some kind of additional supply chain solutions to transport the domestic biomass to the coastal deficit areas. However, also oil may be used as a security of supply fuel with the help of the reserve capacity plants installed in the Finnish networks. (Pöyry Management Consulting, 2019).

3.2 Sector Coupling of Electricity and Heat

Sector coupling of electricity and heat increases the flexibility of the two systems by providing more liquidity to the markets. Especially the increasing amounts of intermittent renewable electricity production cause a growing need for flexibility in the electricity system. In electricity markets, this will cause increased price volatility and occasional low prices. Considering the relatively high thermal inertia in the heating systems compared to the negligible inertia of the power systems, the heating systems may take advantage of the price volatility and the lower prices of electricity. A real-world extreme example of this need is the situation in Northern-China, where huge amounts of wind power are being curtailed during periods of high production due to the lack of sufficient load capacity to make use of the produced electricity (Wang, et al., 2019). In Finland, large heating sector may provide the needed counterpart for this emerging problem.

3.2.1 Sector Coupling Related Studies

Several studies have been made concerning the sector coupling of electricity and heat. Especially, the studies are manifold in Denmark. This is most likely because Denmark has already an extensive amount of variable renewable production in its system and has therefore also been a frontrunner in developing the sector coupling to facilitate a further increase in renewables. In a way, the Danish market conditions may provide a good model for the future system in Finland as well, as the share of renewables is growing.

Dahl et al. (2019) conducted a study about cost sensitivity of optimal sector-coupled systems based on modeling the Aarhus DH system in Denmark. An extensive sensitivity analysis was possible due to a deterministic LP-problem based modeling of the system which is computationally less expensive than e.g. stochastic programming. The study also explores how the optimal system would change in a fossil-free future. The modeling was based on the assumption that the key plants in the production system are reaching their end-of-life. Hence, the investment costs for all the studied technologies were considered. The technologies reviewed in the modeling included well-established production and storage technologies, including boilers, CHP units, heat pumps, and heat storage. (Dahl, et al., 2019).

The results of the study indicate that if fossil fuels are allowed, the cost-optimal production portfolio would include coal CHP, large heat pumps, and heat storage. However, if fossil fuels would not be allowed, the optimal system would consist of only heat pumps and heat storage. The heat pumps would become more favorable with more wind power dominated electricity prices. At the same time, the need for heat storage would increase significantly. (Dahl, et al., 2019).

No biomass CHP or electric or biomass-based boilers would be included in the cost-optimal production portfolio if no restrictions for the capacities were in place. However, considering that there would not be a sufficient amount of heat sources for the heat pumps, the heat pumps would according to the optimization in the study be replaced by electric boilers and a larger amount of heat storage. Only after considering that the electric grids would not allow such a large amount of electric boilers, would the biomass CHP and boilers come in place. (Dahl, et al., 2019).

Nielsen et al. (2016) conducted a study regarding the economic valuation of heat pumps and electric boilers in the Greater Copenhagen DH system. The study assessed the economic value of power-to-heat units by simulating their day-to-day market performance by an operational strategy based on two-stage stochastic programming. The uncertainty in the electricity prices and heat demand in the model was generated with the help of different possible scenarios for the evolution of the variables in the future. In this way, the uncertainty in the decision making that the utilities encounter in the markets is taken into account. To compare the results, a deterministic optimization model of the same problem was made. With the help of the models, the yearly return on potential investments in heat pumps and electric boilers in an existing system was derived. (Nielsen, et al., 2016).

Integrating heat pumps to the DH system of Greater Copenhagen was also studied by Bach et al. (2016). In the CHP dominated system, the modeled heat pumps mainly replaced expensive peak load production and production from the most expensive CHP units. The base load production in the system was provided by the waste incineration CHP plants having negative fuel costs. Thus, as the heat pumps did not provide the actual base load production, the full load hours of the modeled units remained at a moderate level, roughly at 4000 hours. The main heat source for the modeled heat pumps was sea water. (Bach, et al., 2016). According to Pieper et al. (2019), the optimal system performance for heat pumps in the Copenhagen area would be achieved by combining different heat sources, such as seawater, groundwater, and ambient air. The seawater and ambient air heat pumps could be prioritized during the summertime, whereas groundwater during the wintertime. (Pieper, et al., 2019a).

Though the Danish cases provide a good basis for the electrification of DH related studies in Finland, several differences between the countries also have to be taken into consideration. Most of all, these differences include the market and taxation related issues. For example, the taxation policy of power-to-heat technologies is more favorable to electric boilers in Denmark than in Finland. Other differences include e.g. electricity price level and price volatility, and differences in the fuel prices and their taxation, such as natural gas and biomass.

Also, the nature of the study has to be taken into account. For example, the study by Dahl et al. (2019) was conducted from the national economic perspective and did not take into account any taxes for the fuels or price for carbon. Furthermore, the study did not take into account the distribution costs of electricity, which in reality comprises a significant part of the electricity price in Finland. Therefore, especially the fossil-fuel alternatives look much more economical than they look for an individual DH company bound to paying taxes. Also, the power-to-heat technologies were hence much overvalued. Both the studies by Dahl et al. (2019) and Nielsen et al. (2016) used a historical price profile for electricity. Therefore, the electricity price development during the operation period of the modeled plants was not taken into account.

A finding by Nielsen et al. (2016) that the deterministic models overestimate the value of CHP and power-to-heat technologies is worth considering when evaluating the feasibility of the technologies. The main difference originates from operating the heat storage with perfect prognostic versus the real-world conditions. Deterministic models are a good tool in modeling DH systems with variable, such as electricity, price dependent technologies. However, the limitations of this type of modeling have to be taken into account. (Nielsen, et al., 2016).

More advanced operational strategies decrease the gap between real operation and deterministic modeling. The implementation of advanced operational strategies often comes with less cost than investing in new units (Nielsen, et al., 2016). The study also found that parameters, such as COP and differences in electricity price levels substantially affect the profitability of power-to-heat solutions. Especially the effect of electricity price was significant. Thus, a thorough analysis of both the technical performance and electricity price are required when pursuing trustworthy modeling results.

Integrating large-scale heat pumps using low-temperature heat sources to the DH system in Tallinn was studied by Pieper et al. (2019). Especially the seasonal variations in COP for the heat pumps were taken into account. The assessment of cost-optimal amount of heat pumps was made from the private-economic perspective, and the existing plants, including biomass, waste, and natural gas HOB and CHP plants were considered. Based on the results the optimal heat sources to be utilized in the heat pump in decreasing order capacity wise would be sewage water, river water, ambient air, seawater, and groundwater. Together, this optimal amount of heat pumps would supply 16% of the total heat demand in Tallinn. (Pieper, et al., 2019b).

Also, studies concerning the Finnish DH system have been recently conducted. A study by Valor Partners (2016) assessed the commercial potential of using heat pumps as part of DH in Finland. The study included a review of potential implementation options for large heat pumps in DH networks, their benefits and role in the system, theoretical potential, techno-economic feasibility and the restrictions concerning their implementation. Simulations on DH systems including large heat pumps were made for three different sized imaginary systems: small, medium-sized and large. (Valor Partners, 2016).

According to the study, the role of the heat pumps and the profitability of the potential investments vary largely depending on the system it is installed to. In a small system, the heat pumps would replace base load heat production from small and expensive heat only plants. In medium-sized systems including base load CHP production, the heat pumps may help to optimize the CHP production to enhance the system profitability. In larger systems, the heat pumps may interconnect the electricity, heating and cooling systems, and hence provide valuable flexibility to the system as a whole. The study points out that heat pump would be most profitable in this kind of DH system. (Valor Partners, 2016).

It was found that profitable heat pump coverage varies according to the network size. Heat pump coverage of 20-80% of the total heat demand would be economical in smaller systems with only HOB production. In the middle-sized systems, the optimal coverage of heat pumps would be 5-30%, depending on the chosen electricity price level and its profile, and heat storage size. In large systems, the optimal level of the heat pumps would be between 5-15%. It can be noted that if CHP production is included, the optimal coverage of heat pumps in the system will be lower. The variability of the electricity price increases the optimal amount of heat pump production. (Valor Partners, 2016). The study based on an assumption that the existing plants in the system would not be reaching their end-of-life, and thus only the investment costs of heat pumps were considered.

As a major restriction for the deployment of heat pumps in DH systems the study points out the insufficiency of the local power grid to serve the heat pumps. As other restrictions for the deployment, the study states the lack of space for the pumps in downtown areas and the required supply temperatures of the DH networks. As the major risks for deploying the heat pumps the study points out the uncertainty considering the price of the heat source and its persistence, and the uncertainty considering the electricity price development. Especially, if some kind of industrial waste heat is utilized, one has to evaluate whether the heat source will be available for the heat pump for its whole life-time. The high COPs of the heat pumps hedges the heat production to some extent from increases in electricity price. (Valor Partners, 2016).

District heating as part of low-carbon energy systems in the Helsinki region (as well as in Warsaw and Kaunas) has been studied by Hast et al. (2018). It was found that the annual emissions in DH systems in the Helsinki region compared to a reference case could be reduced by 90% by 2050 with an increase of 16% in production costs. The analysis was based on the existing production-portfolio in the area, consisting mainly of gas, coal, and waste-based CHP production. The modeled low-carbon system included mostly a replacement of coal and gas consumption by wood pellets, and to a smaller extent also with wood chips and electricity. The increase in wood pellets usage partly originates from the expected lower cost of rebuilding the existing coal plants to wood pellets plants than building new production capacity. Thus, the amount of heat pump capacity in the modeled system remained moderate, the share of being 14% and 32% in 2030 and 2050, respectively. (Hast, et al., 2018a); (Hast, et al., 2018b). Also, it has to be taken into account that the DH systems in the Helsinki region include heat production by waste incineration providing heat by negative costs for base load production, which further decreases the potential for heat pumps.

The role of heat storages in future district heating systems has been studied by Hast et al. (2017). The modeled system consisted of the connected networks of Järvenpää and Tuusula, comprising a middle-sized Finnish DH system. The cost-optimal dimensioning for the heat storage was found at 1% of annual DH energy, whereas the cost-optimal amount of heat pumps in the modeled system was found at 20% of peak demand. The electricity prices in the study based on future assumptions on power generation, meaning more variable renewable production. (Hast, et al., 2017).

The studies conducted for the Finnish DH systems provide clear benchmarks for the modeling results of this thesis. However, a vast amount of differences between the studies are also apparent, as the studied problem is extremely multidimensional. The assumptions for many of the input values have a huge impact on the results. For example, the electricity price in this thesis is based on the assumptions on future electricity generation capacities and the same weather year as the DH demand. In many of the studies presented above this has not been the case, and historical price profiles for electricity have been used instead. Also, in many of the studies where price profiles based on future assumptions on electricity prices have been used, the electricity price has been somewhat higher than the one used in this thesis.

Furthermore, many of the studies based on the fact that, as the combustion technologies are already present in the systems, the investment costs are only considered for the new units, such as heat pumps. In this thesis, it is assumed that the current production units are coming to their end of life, and hence investment costs of all of the units are included. Also, waste incineration has been used as base load production in many of the systems studied above. No waste incineration is assumed in this thesis, which increases the full load hours of the heat pump investments and their profitability. In the case of heat pumps, the assumptions for the utilizable heat sources and the investment costs related to them represents have a huge impact on the modeling results.

To add perspective, also different development paths for electrification of heating should be shortly discussed, though they are not within the scope of this thesis. A research program EFFSYS EXPAND (2018) consisting of Swedish industry actors, universities and the national energy agency conducted a study considering heat pumps in Swedish DH systems. The proposed alternatives for heat pump implementation in the DH system included new hybrid type of operation schemes, in which the locally installed heat pumps would work in parallel with DH. The project was divided into three sub-projects: 1) heat pumps in combination with DH in manufacturing industry, 2) hybrid heat pumps producing room heating and domestic hot water in parallel with DH, and 3) heat pumps to be used for priming low-temperature district heat (either in low-temperature network or from the return DH water of a conventional network) for domestic hot water production. (EFFSYS EXPAND, 2018).

The approach is much different than when considering large, centrally placed heat pumps feeding the network. Instead, the presented heat pump solutions would feed the load directly at the customers' premises. The solutions still couple the two sectors, as momentary DH and electricity prices would be applicable. The benefits of this kind of system include lower network heat losses as the heat produced by heat pumps does not have to be transferred over a long distance. The solution in the subproject 3 enables the use of return water in the network, which is usually still applicable for the room heating purpose, but not for tap water heating without priming. Furthermore, the lower temperature requirements increase the COP values even for the smaller heat pumps.

A study conducted by (Pöyry Management Consulting, 2016) discussed the role of two-way DH in the future DH systems. Similarly, as in the hybrid solutions presented in the report by EFFSYS EXPAND (2018), the concept would integrate the distributed heat production at customers' premises to the existing DH system. However, in the two-way DH, the customers could also sell any excess heat from their production to the grid. The customers' heat production could partially replace the heat produced by the DH company and thus reduce the fuel usage and need for generation capacity in the network. (Pöyry Management Consulting, 2016).

3.2.2 Electricity Price

As discussed in the previous subsection, the electricity price plays a significant role when assessing the competitiveness of power-to-heat technologies in DH production. For this reason, a future electricity price profile has been used for the analysis in this study. The electricity price profile for 2030 is a sub result from a wider electricity price analysis conducted by Närhi (2020). In the study, different scenarios for electricity prices in Finland are modeled with AFRY's BID3 power market model to find out the electricity market impacts of increased amount of power-to-heat technologies. The profile used in this thesis bases on a base-scenario, in which only a business-as-usual increase in electrification of heating is assumed. The other inputs for the model, such as the production capacity amounts and the fuel and carbon prices, are widely based on government and institution assumptions. Hence, the profile does not represent AFRY's official view of electricity prices in 2030.

BID3 is an optimization model, which finds the cheapest way to balance the demand in all European power markets given. As inputs, the BID3 model has e.g. a plant by plant database for all European countries, multiple historical profiles for weather and demand data to capture any correlation between weather and demand, assumptions on future demand level, interconnection capacity, as well as fuel and carbon prices. As outputs, the model gives e.g. hourly electricity prices for all European price areas, hourly capacity dispatch, flows through the interconnectors and a variety of high-level metrics of the total system. (Pöyry Management Consulting, 2018). An illustration of the BID3 functionality is presented in Figure 21.

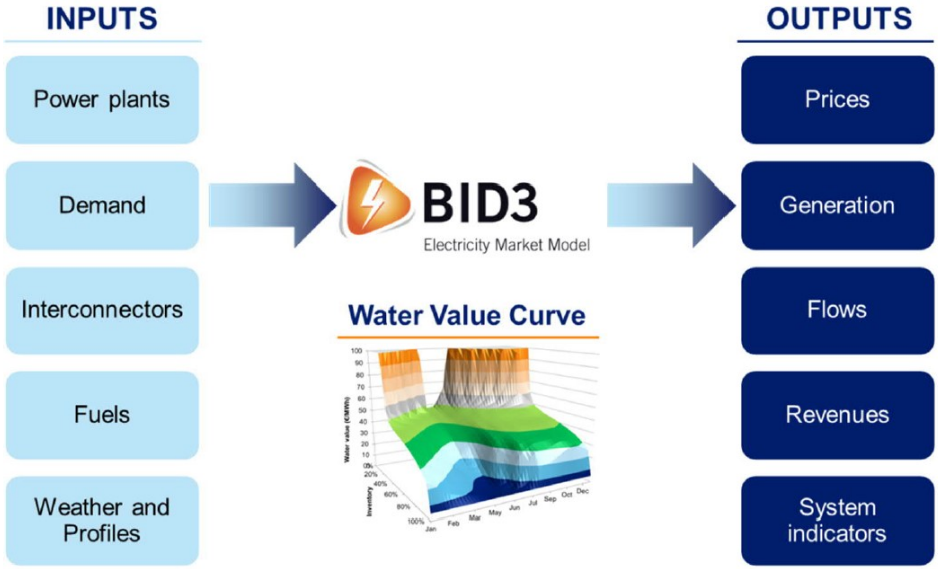

Figure 21. Illustration of BID3 functionality. (Pöyry Management Consulting, 2018).

A physical characteristic of the Nordic electricity markets is its extensive amount of hydropower with significant reservoir capacity. For this reason, the system is prone to energy scarcity and high electricity prices in dry or cold years, and vice versa on the wet and mild years. At the same time, the market is dominated by near-zero marginal cost sources, as around 85% of the generation comes from nuclear, hydro and wind power. If this capacity would always be bid to the market with their near-zero marginal costs, the electricity price would most likely be close to zero quite often during the year. (Pöyry Management Consulting, 2018).

However, the collapse of the prices does not tend to happen as the hydro producers with reservoir capacity may shift their supply during the year to balance periods of high demand (typically winter) and low demand (typically summer). The shift in supply is based on a bidding strategy, where the level at which the production is bid depends on the electricity demand, expectations of the future supply and demand and the cost of alternative sources. The bidding price for hydropower is typically higher if the reservoir levels are low or are expected to become lower in the following months, or if the alternative energy sources are expensive. The same kind of bidding strategy for hydro producers is also used in the BID3 model, including stochastic dynamic programming to handle uncertainty concerning future inflow. (Pöyry Management Consulting, 2018). A simplified water value curve for hydro producers is included in Figure 21.

As a result, the level of the Nordic power prices is set by the opportunity costs of generation, which due to extensive interconnection capacity often is the thermal generation in central Europe. Therefore, though the thermal capacity only represents a small share of the total Nordic production capacity, the coal, gas and CO_2 prices indirectly set the average electricity price level also in the Nordics. (Pöyry Management Consulting, 2018). An illustration of the Nordic power price drivers is represented in Figure 22.

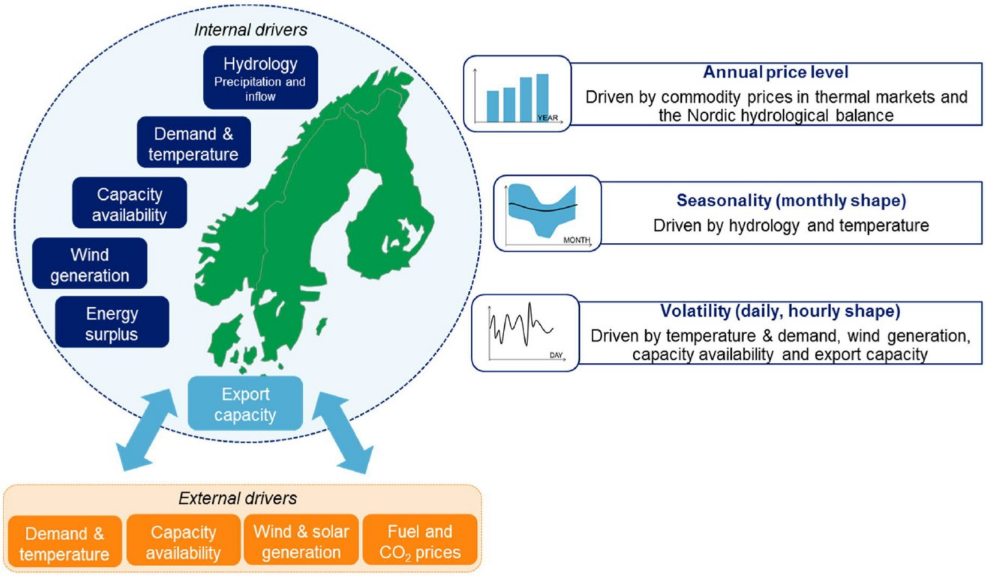

Figure 22. Nordic power price drivers. (Pöyry Management Consulting, 2018).

The pass-through of the commodity and CO_2 prices to the Nordic power prices is decreasing in the future due to increasing amounts of intermittent renewables leading to a larger amount of low price hours in the system. However, according to Pöyry Management Consulting (2018), the pass-through effect will remain relatively high also in the future, as thermal plants are still needed to meet the demand in Europe. (Pöyry Management Consulting, 2018). Though the downward pressure in power prices due to the increasing amount of wind production would be somewhat dampened by this indirect pass-through of prices to the Nordic market, the volatility in the price will most likely increase. This, in turn, would potentially favor the electricity-based heat production if storage capacity is included in the system.

The electricity price profile used in this thesis is based on the historical weather year in 2014, as it represents a fairly average year in terms of hydrological balance. As mentioned before, this leads to a close to average annual electricity price level and seasonal variation. Furthermore, it is the same year as is used for the heat demand profile, which makes the analysis more consistent. As the weather data for the profile is based on real historical data from 2014, the profile may be compared with the historical electricity price profile from 2014. The difference in the profile marks the difference in all the other input assumptions, such as the production capacities, demand, interconnectors and fuels. The profile is a sub result of the study conducted by Närhi (2020), which considered multiple historical weather years in a wider electricity market analysis

In the used future electricity price profile, the main capacity developments in Finland by 2030 compared to 2018 include twice as much nuclear (5.6GW), no change in hydro, almost three times as much wind power (5.5GW), 1.1GW of new solar, and a considerable decrease in thermal from 9.3GW to 7.2GW. The assumed demand increases from 87TWh to 93TWh. At the Nordic level the nuclear capacity remains fairly stable as the decommissioning of Swedish nuclear capacity counterbalances the increase in the Finnish one, the hydro remains almost at the same level, wind more than doubles, solar grows to 5.6GW and thermal capacity decreases significantly from 26.3GW to only 16.6GW. (Närhi, 2020).

The significant increase in Nordic intermittent wind power capacity together with the increase in inflexible and cheap domestic nuclear capacity leads to a notable increase in the number of zero price hours and price volatility. The differences between the historical electricity price profile in 2014 and the used future price profile based on the 2014 weather year is represented in Figure 23. The average price of electricity in 2014 was 36.0EUR/MWh, whereas it in the modeled 2030 scenario would be 44.9EUR/MWh. To increase the clarity of the comparison, a daily profile is presented. The profile used for the modeling is on an hourly basis, and is presented in Appendix 1.

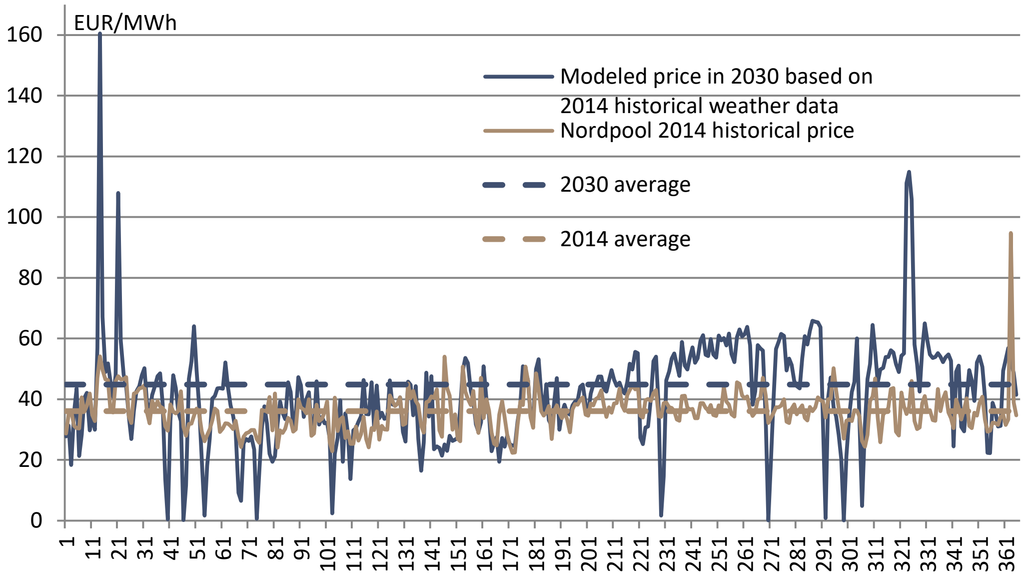

Figure 23. Electricity price for 2030 based on 2014 weather data used in this study and the historical electricity price in 2014. Daily resolution. Sources: (Närhi, 2020); (Nordpool, 2020).

In addition to the energy component of the electricity price, the producer also pays the distribution fee for the electricity consumed and electricity tax. Currently, the tax component for both the heat pumps and electric boilers is 22.5EUR/MWh. However, the current Programme of Marin's Government includes a plan to decrease the electricity tax of industrial-size heat pumps to the EU minimum, 0.5EUR/MWh, in 2020. (Finnish Government, 2019); (European Commission, 2003). Therefore, 0.5EUR/MWh is used for heat pumps in this study. However, the tax for electric boilers in this study stays at 22.5EUR/MWh.

The distribution component varies according to the distribution network where the capacity would be implemented and according to the size of the connection. Figure 24 includes a comparison of distribution prices of five Finnish distribution system operators (DSO) and two different voltage levels for the connections, 20kV and 110kV. The prices are calculated as EUR/MWh basis, including the energy, power and fixed-term components. The energy component is simply paid according to the energy use, whereas the power component is paid according to the monthly peak demand. The fixed component is paid monthly as a fixed lump sum. To simplify the comparison, it is assumed that a 10MW electric load is run constantly during the year producing zero reactive power. As the real full load hours of the production units would not reach this level, the share of the power and fixed components would, in reality, be slightly higher for the power-to-heat technologies assessed in this thesis.

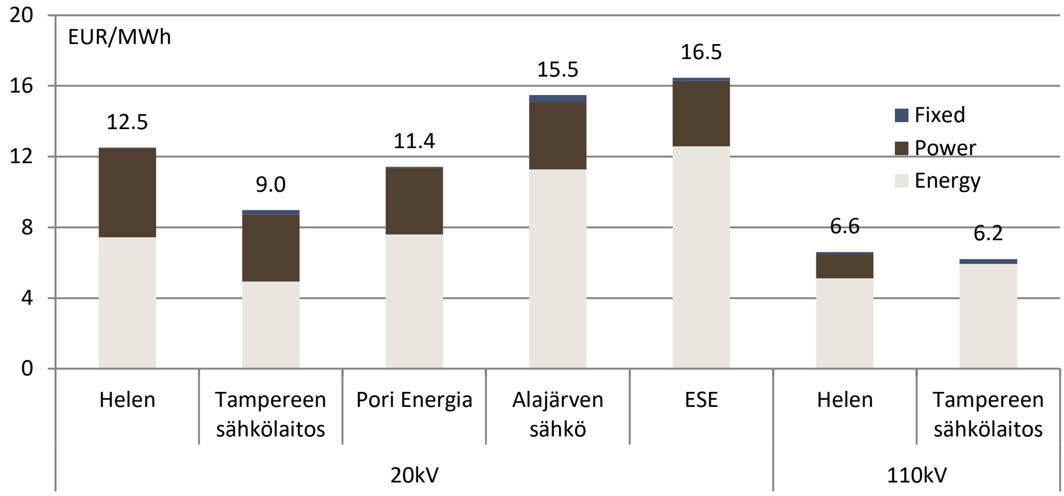

Figure 24. Electricity distribution prices of five Finnish distribution system operators. Sources: (Helen, 2019); (Tampereen Sähkölaitos, 2019); (Alajärven Sähkö, 2018); (Pori Energia, 2017); (ESE, 2019).

If the heat pump is connected to a 20kV network, the distribution price would vary between 9.0-16.5EUR/MWh. The larger DSOs, Helen, Tampereen Sähkölaitos and Pori Energia, have somewhat lower price levels. Furthermore, if it is possible to connect the heat pump to the 110kV network, the price will further drop considerably, being only 6.2-6.6EUR/MWh in Helsinki and Tampere networks. However, the 20kV connections are more realistic for the heat pumps. In this thesis, an energy-based total distribution fee of 12EUR/MWh is considered for both heat pumps and electric boilers. This corresponds quite well to the distribution fee in the larger networks with a 20kV connection.

Considering the comparison of the DSO prices, the assumption of a continuously with full capacity running load is quite realistic for the heat pumps, as they usually have high full load hours. However, the distribution fee for electric boilers would increase a bit from the levels of this comparison due to lower full load hours. If the boiler would be connected to the 110kV network, the error caused by this matter would be much less due to the relatively lower shares of the power and fixed-term components. A connection to a 110kV network would probably be possible if a large amount of other electricity consumption or production is located at the same site.

4 Modeling the District Heating System

A DH system can be modeled in a detailed and technically oriented manner, where the specific structure of the network and the demand points are considered. One example of a more technically oriented DH modeling study is the study by Bach et al. (2016), in which the locations for the plants and demand clusters were considered. Heat pumps serving the transmission system with higher DH supply temperatures and distribution systems with lower temperatures were separately assessed. This was possible, as the study was conducted for a specific network.

Another possibility is to model the network in a more simplified manner to find out the rough economical basis for e.g. new investment possibilities, which is the aim of this thesis. The modeling in this thesis is made for an imaginary average Finnish network and does not account for any spatial details of the technical side considering the network. For example, any production plant can serve any demand in the network and is bound to achieve the same supply temperatures either by themselves or by being primed as any other plants. Though the sufficiency of priming capacity is required in the modeling of this thesis, it does not take into account the locations of the units. Thus, in some cases, priming would in reality not be possible due to the network-specific characteristics regarding the locations of the priming units and the units to be primed.

The modeling of DH systems may also be combined with modeling the electricity system at the same time with the same dispatches of the sector-coupled plants. This enables the modeling to include the price-setting impact of the sector coupled heat production units on the electricity markets. Such modeling based on the Balmorel model was used by Bach et al. (2016), though some kind of simplification in the runs was made.

The other possibility is to model the electricity market separately from the DH dispatch modeling. In this kind of approach, the sector coupled DH producers are price takers from the electricity markets. As the impact of one DH system to the Finnish electricity price can be seen as almost negligible, the approach provides results that are very much precise enough taking into account all the uncertainties with the inputs values used, which leads to much more uncertainty in the final results. The more essential factor is that the electricity price modeling is based on the same weather year, which is implemented in this thesis. Also, as the modeling of the electricity market in the Nordics is fairly complicated as described in 3.2.2, specific importance should be laid on the very fundamentals of the electricity market operation.

The modeling technique itself can be either stochastic or deterministic. Stochastic modeling means that probabilities are included in the modeling, and thus the uncertainties that the producers face regarding e.g. the price of electricity or the weather is taken into account. Hence, this would be a more realistic way to model DH systems, if only the right amount of uncertainty is set for the different model inputs. Stochastic modeling for DH systems was studied by Nielsen et al. (2016). The much more used type of modeling is the deterministic approach, where the perfect foresight for the producers is assumed and no probabilities for the input values are given. Thus, the result is too optimal for the sector coupled production technologies, such as CHP, power-to-heat units and heat storage. The upside with the deterministic approach is the lesser computational effort required, which enables broader analysis in some other dimension with the same effort, such as wider sensitivity analysis or more variables to be optimized.

Most of the studies use a deterministic approach as stochastic modeling requires more computational effort and the degree of stochastics may be hard to define in a realistic manner after all. The deterministic approach gives a good understanding of the problem, but the results must be critically assessed for the production types that benefit from the perfect foresight, such as CHP, power-to-heat technologies, and heat storage. Also in this thesis, the deterministic approach is used.

4.1 The Scenarios and the Objective

To satisfy the DH demand presented in chapter 2.2 different base and peak load configurations and storage size alternatives are evaluated. The assessed base load alternatives include wood chips HOB, wood chips CHP, air-source heat pumps and geo-source heat pumps. The peak load alternatives include wood pellet and electric boilers. The base load alternatives are divided into two main scenarios, where either wood chips HOB or CHP is chosen as the conventional base load production technology. The secondary scenarios include the choice to replace a varying part of this combustion based base load production with either air-source or geo-source heat pumps. The chosen total base load capacity is 80MW.

The tertiary scenarios include also a choice between either wood pellets or electric boiler based peak load production. The chosen total peak load capacity is 78MW. Therefore, in total, we will end up with eight tertiary scenarios (2x2x2 = 8). The secondary scenarios including the choice of the two base load technologies are referred to as "scenarios", whereas the tertiary scenarios with the chosen peak load production technology as well are referred to as "sub-scenarios". The modeled combinations for the production configurations are illustrated in Figure 25.

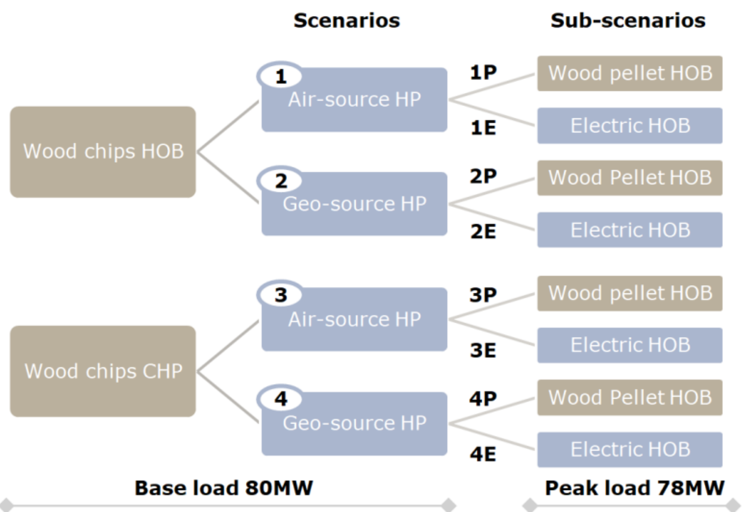

Figure 25. The production portfolio combinations constituting in total 8 sub-scenarios.

All of the sub-scenarios are also calculated with six different storage size alternatives, the sized presenting 0-1.0% heat storage capacity compared to the total yearly DH demand. Furthermore, the amount of heat pumps is also divided into six intervals, the heat pumps presenting 0-100% of the total base load production capacity. As the base load share of the system peak load is roughly 50%, the heat pump capacity may also be considered as 0-50% of the system peak load. Thus, as there are two optimizable matters both having six size alternatives, all of the sub-scenarios will be run in 36 different points. The principle of the dispatch model runs for each sub-scenario is presented in Figure 26.

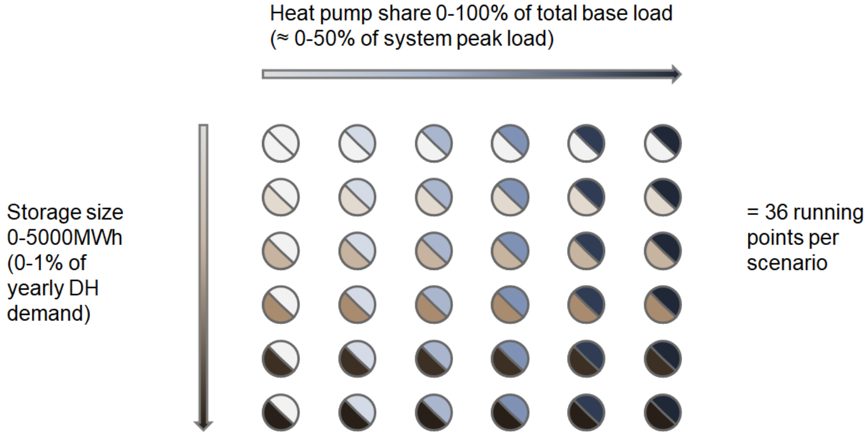

Figure 26. The different running points of the model for all of the 8 sub-scenarios.

The objective of the modeling is to find out the optimal amount of heat pumps in each of the sub-scenarios, as well as the optimal size of heat storage for the production portfolio chosen. Consequently, the sub-scenarios in their optimal running points will then be compared with each other. Thus, the sub-scenarios to be compared may differ significantly from one another in terms of heat pump capacity and storage size, which has to be taken into account in the comparison if also other goals than the economic performance, such as sustainability by decreasing the amount of combustion technologies, is observed.

To assess this point of view, also configurations in which all of the production is based on power-to-heat technologies are compared against the optimal running points of the sub-scenarios. The fully electric configurations mean the sub-scenarios where the peak load production consists of electric boilers in their running points where the base load production fully bases on air-source heat pumps or geo-source heat pumps. Having the HP share of base load production capacity locked in 100%, the running point with the optimal heat storage capacity is then chosen. The optimal and fully electricity-based configurations are compared against each other by their present value (PV) of costs, including the investment costs, the yearly fixed O&M costs as well as the marginal costs obtained from the dispatch model. The principle of the PV calculation is illustrated in Figure 27. The more exact model assumptions are presented in 4.3.

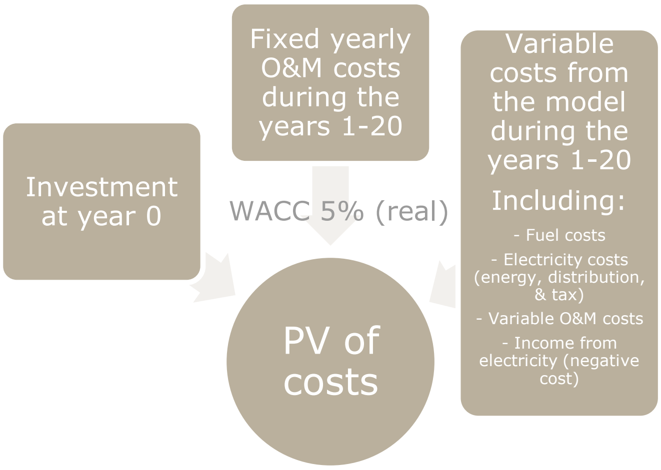

Figure 27. The principle of how the present value of costs for each configuration is calculated from the fixed costs and the yearly variable costs from the dispatch model.

4.2 Model Description

The dispatch model used for this thesis is written in FICO Xpress Mosel mathematical modeling and optimization language. The model is developed by AFRY and further improved in this thesis to e.g. better include heat pump and storage technologies. Using the optimization program and its advanced solvers enable modeling the storage use in an optimized and deterministic way, which would not be possible in a dispatch model written in for example Excel. This is e.g. due to the limitation on the decision variables in the Excel solver.

The inputs for the model include various technical specifications for the production plants, such as their maximum and minimum capacities, the type of the unit for the model to treat the unit in the intended way, inputs for the fuel-specific marginal costs for the units, unit efficiencies, power-to-heat coefficient for CHP units, size of the storage, storage charge and discharge rates as well as storage losses. As hourly profiles, pre-calculated heat demand, electricity price, COP for heat pumps and the supply temperature of the network to make sure that there is enough priming capacity for the low-temperature units at each point in time, such as heat pumps and storage, are given.

As outputs, the model gives the hourly dispatch profiles of the production plants, the hourly storage dispatch and level, and the total yearly variable costs of production. The other costs, including the investment costs and the fixed yearly O&M costs for the units are added to the evaluation later on the process according to Figure 27. This enables the comparison of the total costs of the production portfolio between the different scenarios.

The optimization problem in the model is constructed as a linear programming model. The aim of the model is to minimize the annual operational costs of the described system. Hence, the objective function of the model can be written as:

$$
\min \sum_{h=1}^{H} \Delta t \left(\sum_{u \in HOB\,\&\,CHP} \frac{c_u^{fuel}}{\eta_u} \left(p_{u,h}^{heat} + p_{u,h}^{el}\right) - c_h^{el} p_{u,h}^{el} + \sum_{u \in HP\,\&\,EB} p_{u,h}^{heat} \left(\frac{c_h^{el}}{COP_h} + c_{u,h}^{heat} \right) \right) \tag{7}
$$

The constraints in the model are:

Total system balance

$$
\sum_{u \in prod.units} p_{u,h}^{heat} = p_{tot,h}^{heat}
$$

Maximum and minimum capacities

$$
p_u^{heat,min} \leq p_{u,h}^{heat} \leq p_u^{heat,max}
$$

Storage

$$
0 \leq S_h \leq S^{max}
$$

$$
S_{h+1} = \eta_s S_h + \left(s_h^{in} - s_h^{out}\right) \Delta t
$$

$$
S_{h=1} = S_{h=H}
$$

CHP

below the back-pressure line

$$
p_{u,h}^{el} \leq r_u p_{u,h}^{heat}
$$

below the by-pass line

$$
p_{u,h}^{el} \leq p_u^{heat.max} - p_{u,h}^{heat}
$$

where

H	8760 (the number of hours in a year)
Δt	1 hour
c_u^{fuel}	the unit-specific marginal costs per fuel use (including fuel costs and variable opex) [€/MW_{fuel}]
η_u	the unit efficiency
$p_{u,h}^{heat}$	the heat production of the units during the hour [MW]
$p_{u,h}^{el}$	the power production of the units during the hour [MW]
c_h^{el}	the price of electricity during the hour [€/MW]
COP_h	the heat pump COP during the hour (or EB efficiency)
$c_{u,h}^{heat}$	the unit-specific marginal costs per heat production [€/MW_{heat}]
$p_u^{heat,max}$	the maximum heat production capacity of the unit [MW]

$p_u^{heat,min}$	the minimum heat production capacity of the unit [MW]
S_h	the storage level during the hour [MWh]
S^{max}	the storage maximum capacity [MWh]
η_s	the storage heat loss factor
s_h^{in}	the storage intake during the hour [MW]
s_h^{out}	the storage use during the hour [MW]
r_u	the CHP power-to-heat ratio

Lastly, it is worth to mention, that the dispatch model used is very flexible for changes in all of the aforementioned input and output values as well as the formulas and the working principles described above. This is due to the pure code-based nature of the model. Thus, the described model only represents one version of the model that is particularly tailored for the needs for the examination made in this thesis.

4.3 Model Assumptions

Modeling a DH system includes a high number of assumptions related to the input values of the model. Defining reasonable assumptions is extremely important to obtain rational results from the model. Many of the input values presented in 4.2 are already defined earlier in the study. The hourly demand profile and the network supply and return temperatures are presented in 2.2. The hourly COP profiles for the two heat pump alternatives are presented in 2.3.2.1. The electricity price profile is presented in 3.2.2, and a more accurate hourly profile used in the modeling is presented in Appendix 1. The presented electricity price profile represents day-ahead spot market prices. It is assumed, that the units do not take part in other markets or provide reserve or ancillary services to the grid.

The assumed year of investment is in the range of 2020-2025, and the calculating period for all of the scenarios is 20 years, as presented in Figure 27. The dispatch modeling is only made for the year 2030, which represents quite well the weighted average of the period considering a weighted average cost of capital (WACC) of 5% (real). The cash flow of costs of this year is then assumed to continue as such for the following 20 years after the investment is made. This enables a significantly broader comparison of different setups as well as sensitivity analysis with less computational effort. Calculating the PV with constant cash flows of 2030 leads to almost the same result as modeling the cash flows separately for every year if close to linear changes in the commodity prices, electricity price volatility, and heat demand is assumed.

Technical data and fuel price assumptions for the base load and peak load plants are presented in Table 3 and Table 4, respectively. The fuel prices are based on the analysis made in 3.1. The capital expenditures (capex) represent the specific investment of the chosen technologies. The value is presented per fuel capacity for the combustion technologies and per heat capacity for power-to-heat technologies. The values are mainly based on literature references. However, the assumption for GSHP capex is based on the analysis made in 2.3.2.1.

The operation and maintenance costs (O&M) are divided into fixed and variable costs and are based on literature estimates. The fixed costs represent the operation and maintenance related costs that occur regardless of the utilization rate of the unit, whereas the variable costs depend on the level of utilization. The efficiencies of the units (η) and the power-to-heat ratio of the CHP plants are based on literature estimates. The power-to-heat ratio represents the share of electricity production of the plant compared to heat production and depends on the size of the chosen turbine. The chosen ratio represents a relatively common ratio for the electricity production and does not consider the electricity used by the plant itself as power production of the plant. The max temperatures of the heat pump units are based on the literature review in 2.3.2.1.

Technology	Fuel price [€/MWh]	Capex [€/kW$_{fuel}$]*	Lifetime [years]	O&M fixed [k€/MW$_{fuel}$/a]	O&M variable [€/MWh$_{fuel}$]	η/COP [%]	Power-to-heat ratio (net)	Max temp. [°C]
Wood chips HOB	24.2	790	20	22	2.7	115	-	-
Wood chips CHP	24.2	1050	20	30	1.1	111	0.33	-
Air-source heat pump	-	700*	20	2	3.2	~2.6	-	90
Geo-source heat pump	-	1800*	20	2	3.2	~3.0	-	90

Table 3. Technology and cost data for the chosen base load technologies (Hast, et al., 2017; Pieper, et al., 2018; Danish Energy Authority, 2016).€/kW$_{heat}$ for power-to-heat technologies.*

Technology	Fuel price [€/MWh]	Capex [€/kW$_{fuel}$]*	Lifetime [years]	O&M fixed [k€/MW$_{fuel}$/a]	O&M variable [€/MWh$_{fuel}$]	Efficiency / COP [%]
Pellet HOB	38.0	300	20	10	1.9	92
Electric boiler	-	100*	20	1	0.8	99

Table 4. Technology and cost data for the chosen peak load technologies (Danish Energy Authority, 2016). .€/kW$_{heat}$ for power-to-heat technologies.*

Not all of the aforementioned technical inputs values are used by the dispatch model itself, as the dispatch model only consider the marginal costs of the units. Values included in the total PV calculation after the dispatch model run include the capex costs, lifetime of the units, and the fixed O&M costs. This is because these costs occur in any case if the technology has been chosen.

5 Findings

In this chapter, the results of the modeling are presented. These include the PV of the costs of different scenarios in all model running points and pointing out the most profitable share of heat pumps and heat storage in each sub-scenario. Also, the dispatch profiles of the production units and the storage use are presented and insights based on the profiles are enumerated. The analysis of dispatch profiles is also extended to electricity only based scenarios, which represents the running points of the sub-scenarios with zero chosen combustion-based production capacity.

Lastly, the PV values of the costs of the scenarios are compared between the optimal running points of each sub-scenario as well as the electricity only scenarios. The same comparison is also made as the production costs per heat produced basis, as this kind of comparison gives a better understanding of the real cost differences between the scenarios if the competitiveness against alternative heating types is considered.

5.1 Scenario 1: HOB and ASHP

The base load production in the first scenario consists of wood chips HOB production as conventional combustion technology and air-source heat pumps as an alternative non-combustion technology. The total capacity of the base load units is 80MW. Furthermore, both wood pellets and electric HOB are considered as peak load production, with a fixed capacity of 78MW.

If wood pellets HOB is chosen as the peak load technology, the optimal base load production configuration in the first scenario would be air-source heat pump coverage of 60% of the base load production, the rest being wood chips HOB. The feasibility of the configuration sharply increases when 20% of heat pumps are included compared to a situation where no heat pumps would be commissioned. However, the cost-effectiveness remains quite stable at 20-80% and even at 100% heat pumps coverage of base load production. The cost-optimal coverage of 60% heat pumps of base load production capacity would result in approximately 30% of the system peak load.

Furthermore, the cost-optimal configuration would include 2000MWh heat storage, the size being 0.4% of the yearly heat demand of the system. Storage larger than this would not lead to cost savings that would suffice the investment costs of additional storage. The cost-optimal configuration would result in present value (PV) of the costs of 256MEUR. The simulation results for the configuration are presented in Figure 28.

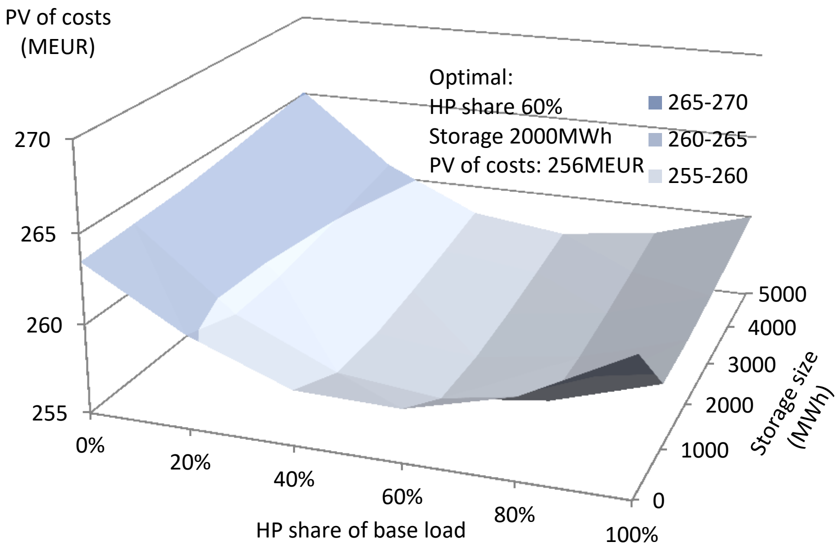

Figure 28. Simulation results for the configuration wood chips HOB, air-source heat pump, and wood pellets boiler.

The production dispatch profile and storage use of the cost-optimal configuration is presented in Figure 29. It can be noted that the storage is not large enough to cover the peak load production during the periods of highest demands, but is used for peak shaving during peak load hours within periods of lesser demand. Furthermore, the storage is used to take advantage of the changing electricity prices for heat pump production during the summer.

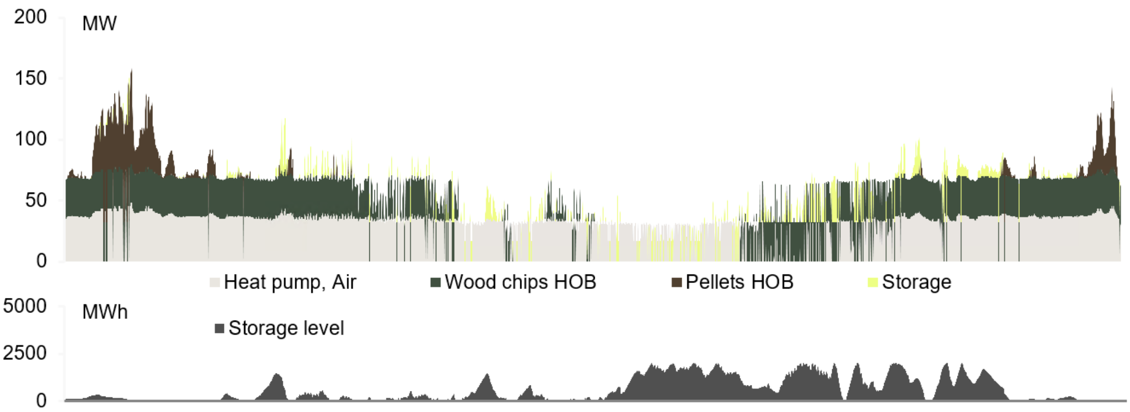

Figure 29. Production dispatch and storage use for the cost-optimal dimensioning of the configuration wood chips HOB, air-source heat pump, wood pellets boiler, and heat storage.

If electric HOB is chosen as the peak load production technology for the first scenario, the optimal base load production configuration would include slightly lower air-source heat pump coverage of 40%. The cost-effectiveness still remains quite stable at 20-80% heat pumps coverage of base load production. Compared to the first scenario with pellets as peak load production capacity, adding at least a small amount of heat storage clearly leads to better system profitability. The benefits increase together with increasing heat pump share in the system. The cost-optimal heat storage size would be 4000MWh equaling to 0.8% of the yearly heat demand of the system.

The cost-optimal configuration would result in a PV of the costs of 239MEUR. Thus, the electric boiler in the configuration would lead to lower total costs than wood pellets HOB as peak load production. This partly originates from the lower investment costs for the electric boilers. The simulation results for the configuration are presented in Figure 30.

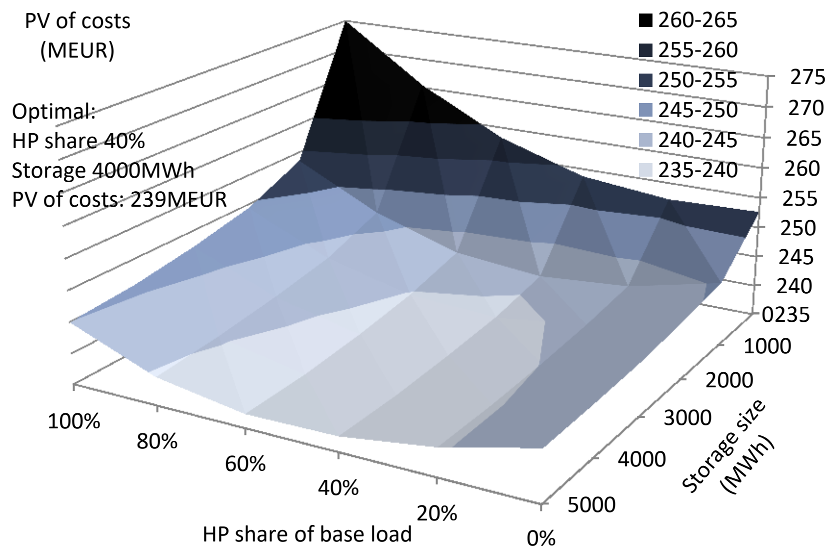

Figure 30. Simulation results for the configuration wood chips HOB, air-source heat pump, and electric boiler.

The dispatch profile of the cost-optimal configuration with electric boilers is presented in Figure 31. Differing from the dispatch profile with pellets as peak load production, the storage, which is also double the size, is now used much more. This is much because of the possibility to utilize the electricity price volatility to a greater extent with the electric boiler benefiting of the low electricity prices in addition to the heat pump. The electricity price volatility leads to much wider utilization of the large heat storage during the peak load hours than with the pellets production having constant marginal costs for heat production. If no heat storage would be included, the electric boiler would be forced to be used at the very highest electricity price peaks as well, which often occurs during the high heat demand periods.

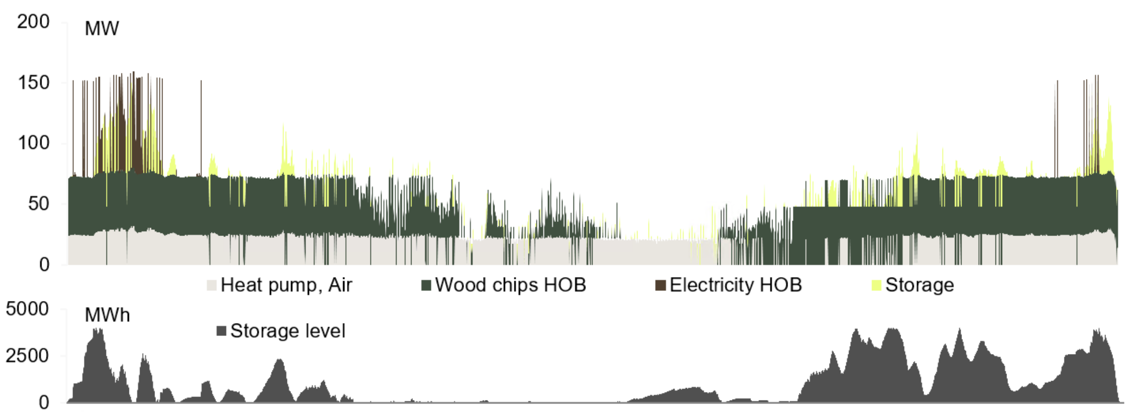

Figure 31. Production dispatch and storage use for the cost-optimal dimensioning of the configuration wood chips HOB, air-source heat pump, electric boiler, and heat storage.

5.2 Scenario 2: HOB and GSHP

The base load production in the second scenario consists of geo-source heat pump production supplementing the conventional heat production with wood chips HOB. Also here, both wood pellets and electric HOB are considered as the peak load production technology.

The optimal base load production configuration with wood pellets as peak load production would include no heat production with geo-source heat pumps. In fact, the total system costs would increase quite steeply when heat pumps are added. This is due to the relatively high investment costs of the geothermal wells which increase the specific investment costs of geo-source heat pumps significantly. The investment costs of the geothermal wells were included in the analysis in 2.3.2.1.

No heat storage would either be included. The lack of production technologies having a constantly variable fuel price is the explaining factor here, as no price arbitrage by producing and storing for later use can be made. Furthermore, as the pellet production is not that much more expensive than wood chips HOB production, the heat storages would not pay back their investment costs by peak shaving. However, they do decrease the marginal costs of the system slightly, as the present value of the costs of the system stays almost constant with any amount of heat storage. The cost-optimal configuration would result in a PV of the costs of 263MEUR. The simulation results for the configuration are presented in Figure 32.

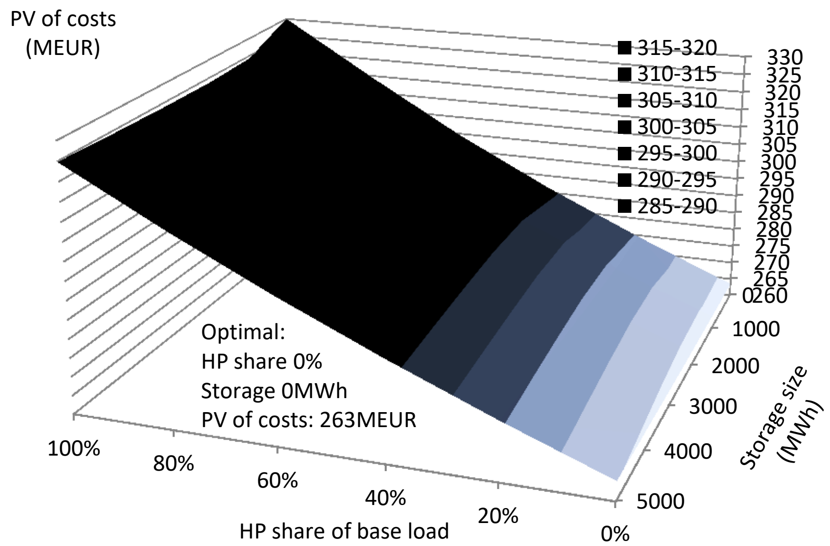

Figure 32. Simulation results for the configuration wood chips HOB, geo-source heat pump, and wood pellets boiler.

The dispatch profile of the cost-optimal configuration is presented in Figure 33. As the cost-optimal configuration did not include any heat pumps, the profile eventually represents a scenario in which only wood chips HOB alone is chosen as the base load technology. It can be noted that the results are the same as what would be obtained with a predestined dispatch order for the plants. This is due to the lack of variable price production technologies and heat storage in the system.

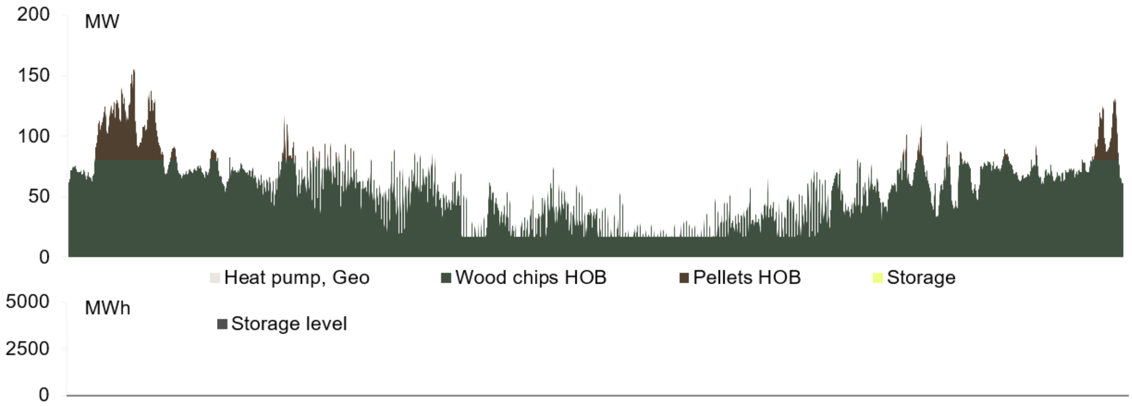

Figure 33. Production dispatch and storage use for the cost-optimal dimensioning of the configuration wood chips HOB, geo-source heat pump, wood pellets boiler, and heat storage.

No geo-source heat pumps would be included in the second scenario either with electric boilers as peak load production. The total system costs would increase roughly as steeply with an increased amount of heat pumps as if pellets were used as peak load production. However, the optimal amount of heat storage would rise to 4000MWh. Adding a heat storage capacity of 1000MWh reduces the PV of the costs by several million euros, whereas further addition only slightly reduces the costs. The cost-optimal configuration would result in a PV of the costs of 244MEUR. The simulation results for the configuration are presented in Figure 34.

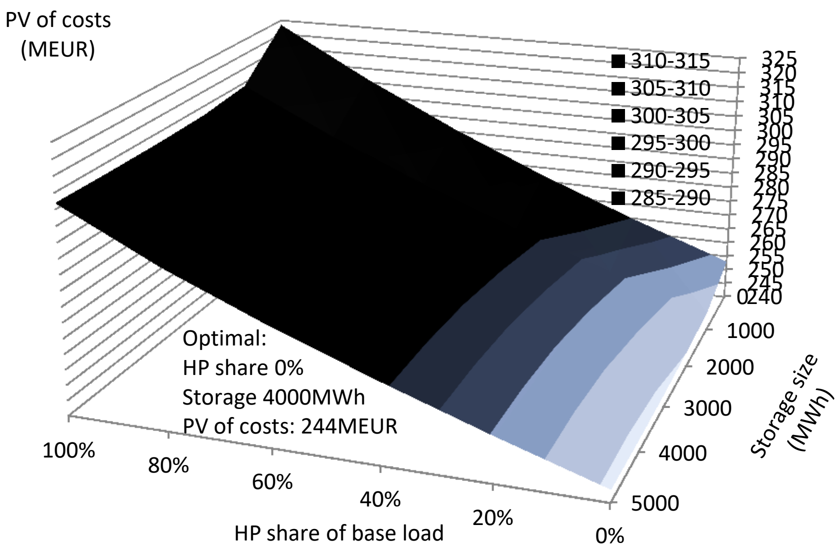

Figure 34. Simulation results for the configuration wood chips HOB, geo-source heat pump, and electric boiler.

From the dispatch profile in Figure 35, we can see that the storage is indeed utilized in peak shaving in the system. Though the storage is not large enough to fulfill the entire peak load production, it still replaces a significant amount of the production with electric boilers. Also, the use of electric boilers is shifted to less expensive hours close to the peak demand hours. Thus, price arbitrage and peak shaving are actually made in parallel. No electric boilers would be used outside peak load hours. Hence, it can be deduced that price arbitrage would not be profitable whenever there are still moderately priced base load production, such as wood chips HOB production, in the system. This is because that the inevitable electricity tax and distribution costs already exceed the marginal costs of wood chips HOB production.

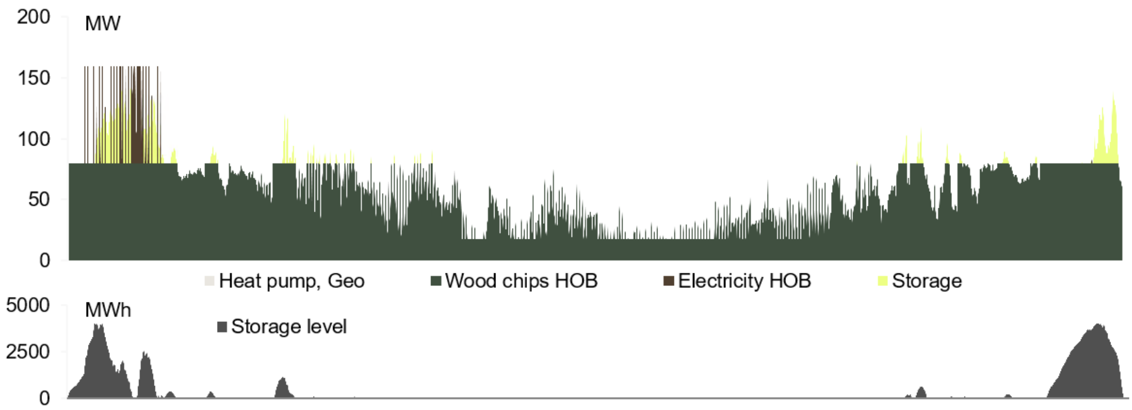

Figure 35. Production dispatch and storage use for the cost-optimal dimensioning of the configuration wood chips HOB, geo-source heat pump, electric boiler, and heat storage.

5.3 Scenario 3: CHP and ASHP

In the third scenario, wood chips CHP production is considered as the conventional combustion technology instead of HOB production. The supplementing heat pump technology is air-source heat pumps.

With wood pellets HOB as the chosen peak load technology, the optimal base load production configuration in the third scenario would be air-source heat pump coverage of 60% of the base load production. Thus, the optimal amount of air-source heat pumps is the same as if wood chips HOB as the supplementing combustion technology. The feasibility of the configuration is much more sensible for changes when deviating from this optimum than when HOB base load was considered. This indicates much stronger synergies with the two base load technologies (CHP and heat pumps), as including only one of them would lead to much higher total costs on system level. It is noteworthy, that especially having only CHP in the system would lead to significantly higher costs than when also heat pumps are included in the system.

Also, the optimal size of the storage is the same as if wood chips HOB were chosen as the combustion technology, being 2000MWh. However, the total costs of the system decrease much sharper with a small addition of storage in scenario 3 than in scenario 1 with base load HOB. Thus, it can be pointed out that scenario 3 with CHP also benefits much more of the storage than scenario 1 with HOB. Storage larger than this would not decrease the cost further, but would not increase them much either. The cost-optimal configuration would result in a PV of the costs of 254MEUR. The simulation results for the configuration are presented in Figure 36.

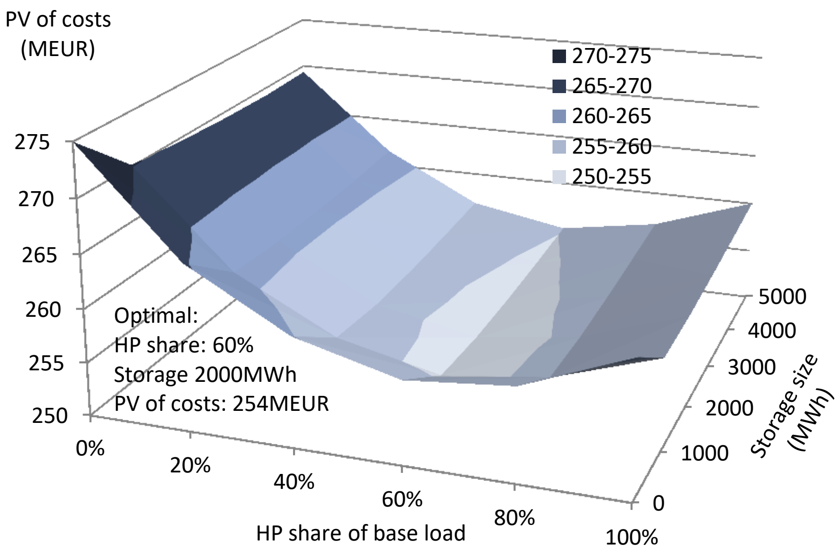

Figure 36. Simulation results for the configuration wood chips CHP, air-source heat pump, and wood pellets boiler.

Figure 37 presents the dispatch profile of the cost-optimal configuration in scenario 3 with pellets as peak load production. It can be noted that the production from the CHP and heat pump units can be alternated during the low demand hours according to the electricity price in the markets. This is one clear origin of the synergies between the technologies, as they smoothly complement each other, the one producing, and the one consuming electricity. However, the synergies between an extraction-condensing CHP capacity and heat pumps would most likely be even higher than the ones obtained here with the backpressure CHP, as the former one can slightly increase electricity production by discarding heat production in case of high electricity prices.

The heat storage is not much used for peak shaving. Instead, the heat storage enables full electricity production for the backpressure CHP plants during the hours of low heat demand but high electricity prices. Concurrently, heat pumps can be run with higher capacities during the hours with low electricity prices. Thus, the inclusion of heat storage increases the potential of the two technologies to complement each other even further.

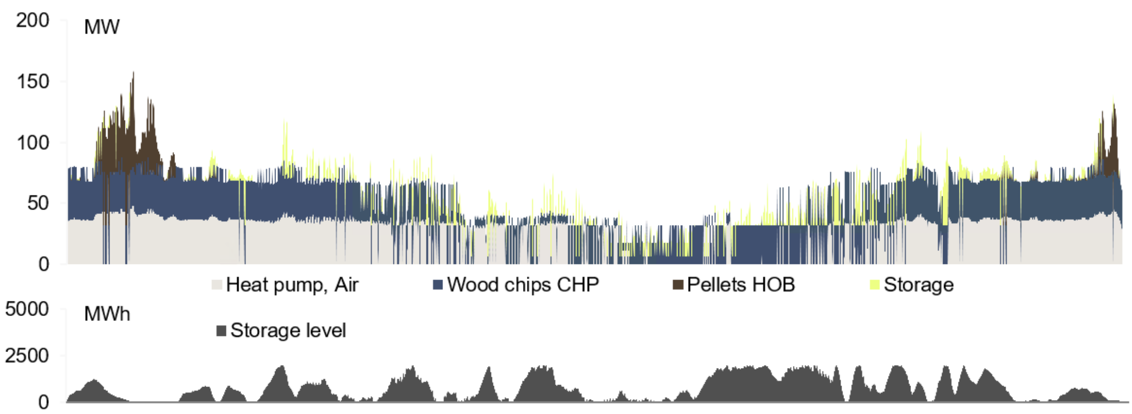

Figure 37. Production dispatch and storage use for the cost-optimal dimensioning of the configuration wood chips CHP, air-source heat pump, wood pellets boiler, and heat storage.

With electric HOB as peak load technology in the third scenario, the optimal base load production configuration would include less heat pump capacity and more heat storage, 40% and 5000MWh, respectively. Actually, the optimal storage size could even be larger than this, as the 5000MWh size was the largest that was modeled. However, it would most likely not be much larger, as the cost-optimality is sloping very gently even from 4000MWh to 5000MWh. Again, adding at least 1000MWh of storage is the crucial step here, and the further storage additions are more or less fine-tuning.

Compared to the same scenario with pellets as peak load production, it is noteworthy that the difference in costs between having only heat pumps or only CHP as base load production is much smaller. This is due to that CHP already has complimentary benefits from the chosen peak load type, and the inclusion of heat pumps to the system is not as essential as if the peak load production would also be combustion-based. The cost-optimal configuration would result in a PV of the costs of 234MEUR. The simulation results for the configuration are presented in Figure 38.

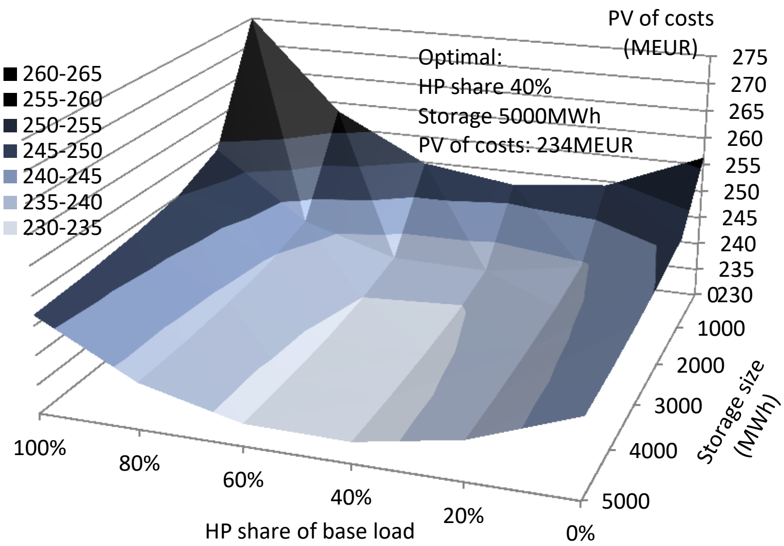

Figure 38. Simulation results for the configuration wood chips CHP, air-source heat pump, and electric boiler.

From Figure 39 it can be noted that the storage is utilized again much for peak shaving when electric boilers are chosen. Much of the energy used for charging the storage originates from by-passing the turbines of the CHP plants. This can be seen as temporarily higher heat production capacities for the CHP units in the dispatch profile. In practice, this allows the producer to produce heat with the price of lost electricity incomes. Thus, by-passing the turbine leads to cheaper heat production than electric boilers which include costs from electricity distribution and tax. Hence, it is also often profitable to by-pass the turbine outside the peak load hours. This might be one reason why the optimal amount of CHP in the system was more than when pellets were used as peak load production, as by-passing the turbine together with heat storage enables the electric-boiler-backed system to better survive the peak load hours with higher electricity prices. In comparison, when pellets based peak load capacity is used, the marginal costs during the peak load production would remain moderate even without a charged storage.

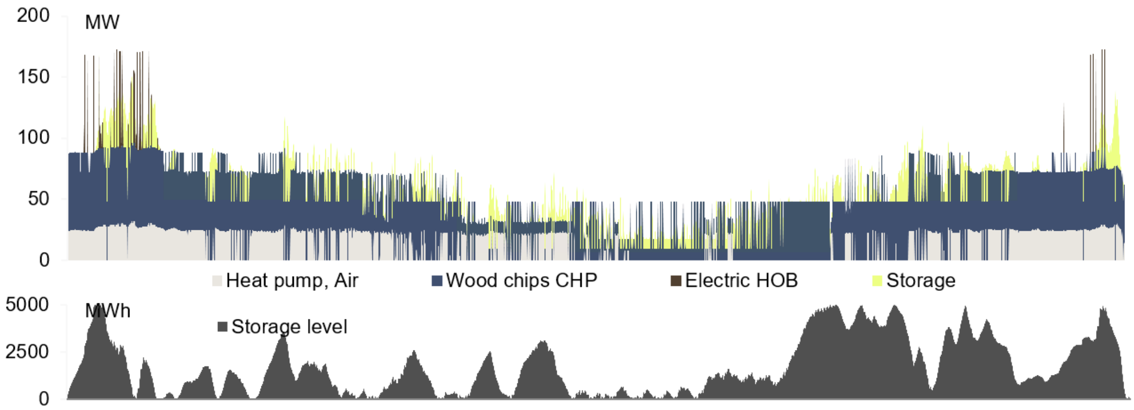

Figure 39. Production dispatch and storage use for the cost-optimal dimensioning of the configuration wood chips CHP, air-source heat pump, electric boiler, and heat storage.

5.4 Scenario 4: CHP and GSHP

In the fourth scenario, the supplementing heat pump technology for CHP production is geo-source heat pumps.

Similarly, as in the second scenario with wood chips HOB as the combustion-based base load technology, no geo-source heat pumps would be included in the cost-optimal system in the fourth scenario. However, the increase in the total costs would not be as steep as in the second scenario if heat pumps were added to the system. Nevertheless, this only applies to a small amount of heat pump capacity, approximately 20%. After this, the costs would increase more steeply. This may be explained by the same synergies between heat pumps and CHP as mentioned in the previous subsection. The optimal amount of storage would be as high as 4000MWh. However, again, the benefits of further storage after 1000MWh are not that large. The cost-optimal configuration would result in a PV of the costs of 269MEUR. The simulation results for the configuration are presented in Figure 40.

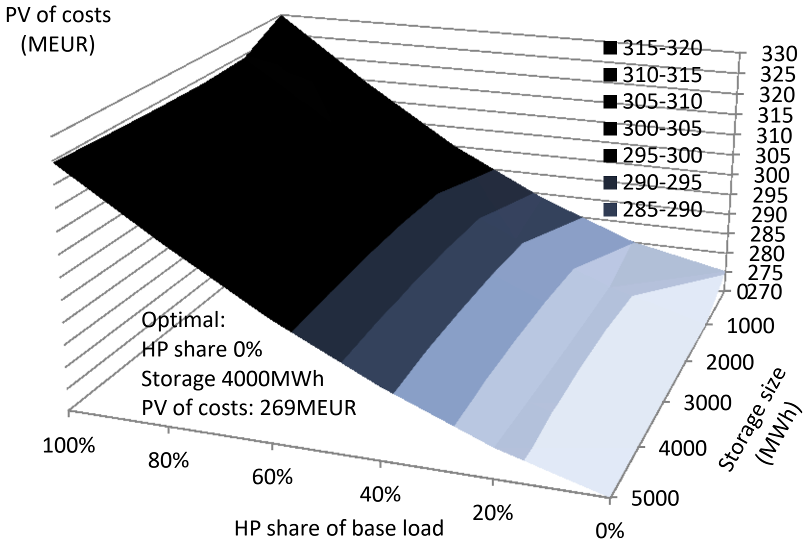

Figure 40. Simulation results for the configuration wood chips CHP, geo-source heat pump, and wood pellets boiler.

The dispatch profile of the cost-optimal configuration is presented in Figure 41. As in the second scenario with HOB capacity supplemented with potential GSHP capacity, no GSHP is included in the profile. Thus, the dispatch profile represents wood chips CHP alone as base load capacity. It can be seen that the CHP plant utilizes the storage widely during the whole year.

The ramping of the plant according to the electricity prices leads to a significantly higher capture price of the sold electricity for the CHP owner. In principle, such ramping is possible from a technical perspective. For example the Danish Energy Authority (2016) lists in their technology data catalogue that CHP plants are able to regulate their capacity by 4% per minute when the plant is running. This means, that if the plant is running at the minimum of 20% of its capacity, it takes 20 minutes to reach the maximum capacity. Thus, the depicted ramping should be possible, as we are using an hourly model. However, such a perfect ramping according to the electricity prices would require very high-end operational strategies and control devices for the plant. In addition, as discussed in Chapter 4, perfect foresight for the CHP producer is not quite realistic. Hence, the model overestimates the value of CHP as the production technology slightly.

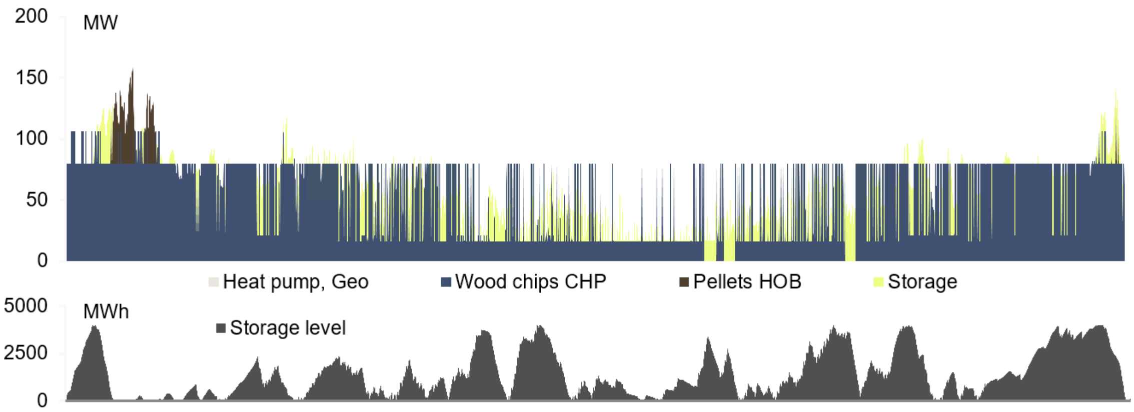

Figure 41. Production dispatch and storage use for the cost-optimal dimensioning of the configuration wood chips CHP, geo-source heat pump, wood pellets boiler, and heat storage.

With electric boilers as peak load capacity in the fourth scenario, no geo-source heat pumps would still be included in the cost-optimal system. The largest modeled storage capacity would be the most cost-optimal for the system as in the other scenarios with peak load production with electric boilers. Differing from the fourth scenario with pellets as the peak load production technology, adding even a small amount GSHP into the system would increase the costs almost as steeply as the further amounts of GSHP capacity would. This is most likely because the expensive electricity-based peak production can be replaced by by-passing the turbine before the peak load hours and utilizing the storage to save this heat to the hours of high demand. This leads to added benefits for incremental CHP capacity. Also, the system already includes electric boilers as a power-to-heat technology providing some small synergies for the CHP production. The cost-optimal configuration would result in a PV of the costs of 243MEUR. The simulation results for the configuration are presented in Figure 42.

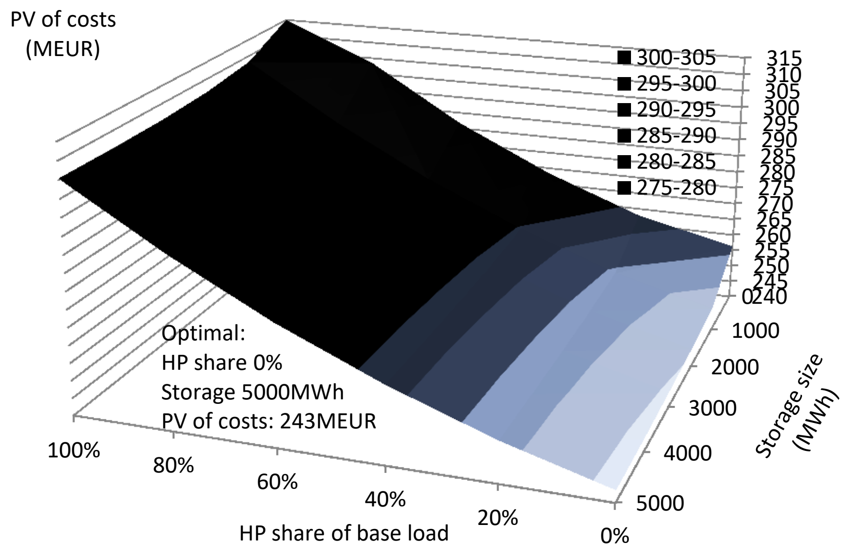

Figure 42. Simulation results for the configuration wood chips CHP, geo-source heat pump, and electric boiler.

The dispatch profile and storage use for the fourth scenario with electric boilers as peak load technology is presented in Figure 43. It can be noted, that almost no electric boilers are used in the yearly dispatch. Instead, the turbines of the CHP units are by-passed during and before the peak load hours. The ramping of the CHP plant remains as high during the year as in the case of pellets as peak load capacity.

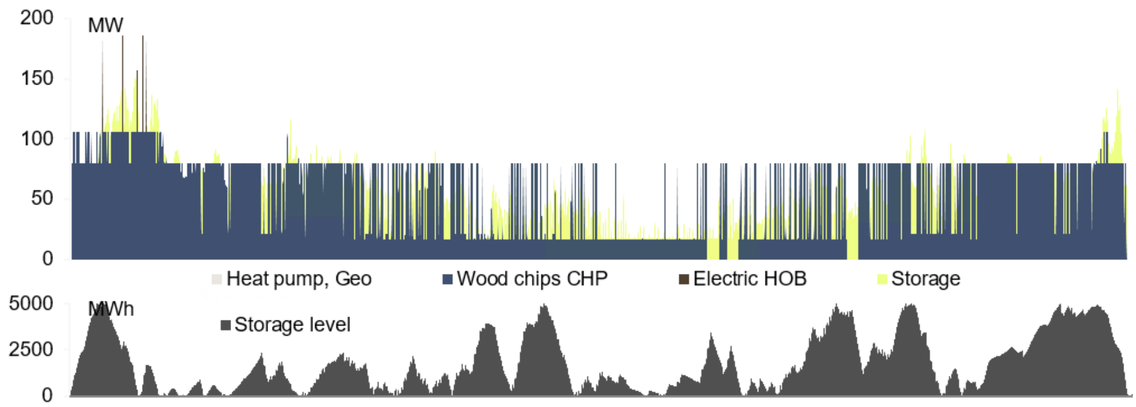

Figure 43. Production dispatch and storage use for the cost-optimal dimensioning of the configuration wood chips CHP, geo-source heat pump, electric boiler, and heat storage.

5.5 Fully Electricity-based Alternatives

Here, the dispatch profiles of the fully electricity-based alternatives are presented. These alternatives represent the scenarios where electric boilers are chosen as the peak load production technology and the base load production is fully provided by heat pumps. Thus, these scenarios only represent two alternatives, where either air-source or geo-source heat pumps are used as base load production together with peak load electric boiler production. The most profitable storage size according to the optimization is chosen for the evaluation.

The dispatch profile for the fully electricity-based alternative with air-source heat pumps as base load production is presented in Figure 44. The most optimal storage size would be 5000MWh or larger, as this was the largest modeled size for storage. However, Figure 28 and Figure 38 shows the total costs would not decrease very steeply with further storage additions, though the fully electricity-based scenario would still benefit from further storage. It is worth to notice, that the heat storage is not used much during the highest peak load hours. This is due to the low supply temperature levels of both the modeled heat pumps as well as the storage. Thus, electric boilers are required to be used regardless of the electricity prices during these hours, as no combustion-based technology is available for priming.

Here it can also be seen clearly that the heat pump capacity varies somewhat during the year. This is due to the fact that the temperature change of the cold source at the heat pump evaporator remains constant during the operation, which leads to constant ambient energy utilization at maximum capacity. However, as the COP of the air-source heat pumps significantly varies during the year, the electricity intake and thus its contribution to the total heat production also varies during the year. Consequently, the production capacity of the heat pump varies during the year. The design point for the capacity is the peak load hour of the year, during which the COP is usually at its lowest and the electricity consumption at its highest. This also leads to a slightly wider utilization of electric boilers during the year, as the heat pump capacity is lower outside the design point. A similar effect is also visible with geo-source heat pumps but is not as evident, as the COP variation during the year is much lower. The fully electricity-based alternative with air-source heat pumps as base load production would lead to a present value of 247MEUR.

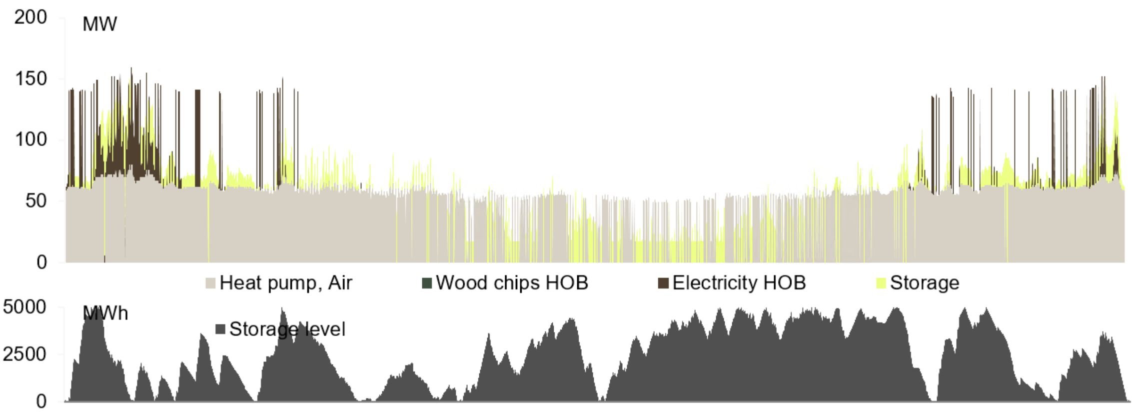

Figure 44. Production dispatch and storage use for the electricity only configuration with air-source heat pumps as base load production and electric boilers as peak load capacity.

The dispatch profile for the fully electricity-based alternative with geo-source heat pumps as base load production is presented in Figure 45. The optimal storage size would be 4000MWh. Compared to the fully electric alternative with air-source heat pumps where larger storage size was profitable, this most likely result from the fact that the geo-source heat pump provides heat at much more stable capacity thorough the year as it operates with a more stable COP.

Here again, it can be noted, that electric boilers are especially needed for priming the heat pump and storage output. Thus, the use of the electric boilers cannot that well be optimized according to the electricity prices, also reducing the need for further storage. Thus, if the other technologies in the system do not reach the required supply temperatures of the system and electric boilers are needed mostly for priming these units, the profitability of electric boilers drops significantly. Hence, it would be optimal if the need for priming would be decreased either by higher achieved supply temperatures by the production units or by lowering the required supply temperature. The required supply temperature could be lowered e.g. by placing heat pumps to the branches of the network closer to the customers and thus lowering the heat losses that occur.

It is also noteworthy, that though the use of electric boilers is not much optimized according to the electricity prices, the use of the heat pump much is. Especially during the period of lower demand, the ramping of heat pumps is very significant. As discussed in 2.3.2.1, the high level ramping of heat pumps may lead to faster wear of sensitive components such as the compressor. However, this may also change if the heat pumps would be designed for this kind of operation in the future. Also, it is worth to notice, that the main wear for the heat pumps from a high level of ramping would most likely occur if the heat pumps would be used in the balancing markets with an even higher frequency of ramping rather than in the day-ahead markers such as in this study.

The main issue to be considered may be the same as for CHP that how far is this optimal heat pump operation from the actual level of operational optimality taking into account the uncertainties in the real operation and the insufficiencies in the operational strategies in pursuing the optimal dispatch. The fully electricity-based alternative with geo-source heat pumps as base load production would lead to a present value of 307MEUR.

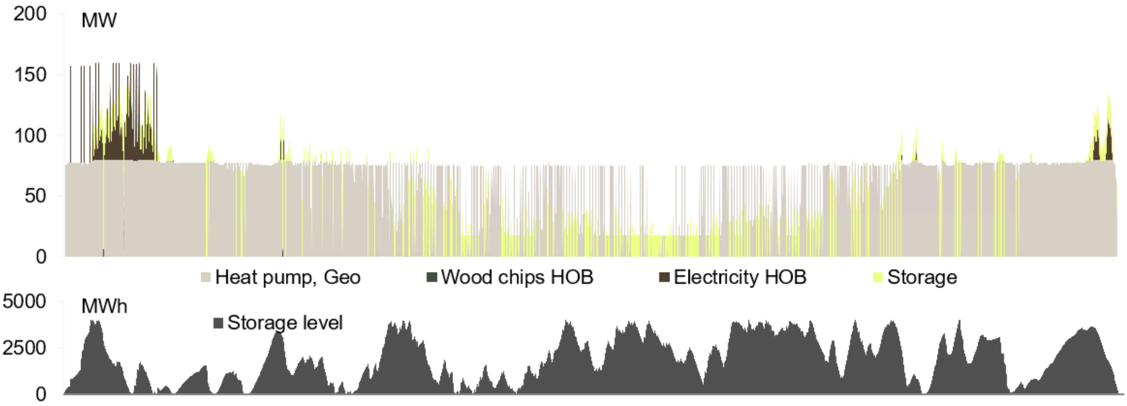

Figure 45. Production dispatch and storage use for the electricity only configuration with geo-source heat pumps as base load production and electric boilers as peak load capacity.

5.6 The Results

According to the cost optimizations, the optimal amount of air-source heat pumps would be 60% and 40% of the base load capacity with pellets and electric HOB chosen as the peak load production technology, respectively. The results are the same regardless of whether wood chips HOB or CHP are used as the conventional combustion-based technology besides the heat pumps. However, the CHP alternative benefits slightly more of the larger storages. The benefits of larger storage sizes are even more evident when the pellets boilers as peak load capacity are replaced with electric ones.

The optimizations also showed that no geo-source heat pumps would be installed beside the conventional combustion technologies if only cost-optimality is pursued. This is due to the high investment costs of the technology, especially the ones of the drilling phase. Therefore, the combinations with possible geo-source heat pumps only represent wood chips HOB and CHP plants as base load production, and an optimized amount of storage. The HOB scenario with pellets as peak load production would include no storage, whereas the other scenarios require a large amount of storage to reach their cost-optimality.

Figure 46 represents the comparison of the present values of the cost-optimal configurations of the main scenarios as well as the ones of the fully electricity-based alternatives. Firstly, it is noticeable, that the electric boiler is the more cost-optimal choice as peak load production in all of the scenarios. This is especially due to the lower investment costs of the electric boilers, which can be seen as the smaller dark area in the stacked bar in Figure 46 representing the fixed costs of each scenario, including mainly investment costs but also the fixed O&M costs.

Though HOB alternative would be more profitable than CHP without heat pumps when pellets are used as peak load capacity, the cost difference between the two technologies disappears when the peak load production is changed to electric boilers. This is especially because the expensive production with electric boilers is not much needed in the CHP alternative, as by-passing the turbine together with the heat storage provides cheaper production during the high demand hours. The most profitable alternative is a combination of CHP and 40% of ASHP of base load capacity and electric boilers as peak load production. For comparison, the best HOB scenario where also 40% of base load production is ASHP has a PV of the costs of 5MEUR higher. Therefore, there are more synergies between the CHP and ASHP technologies than between HOB and ASHP.

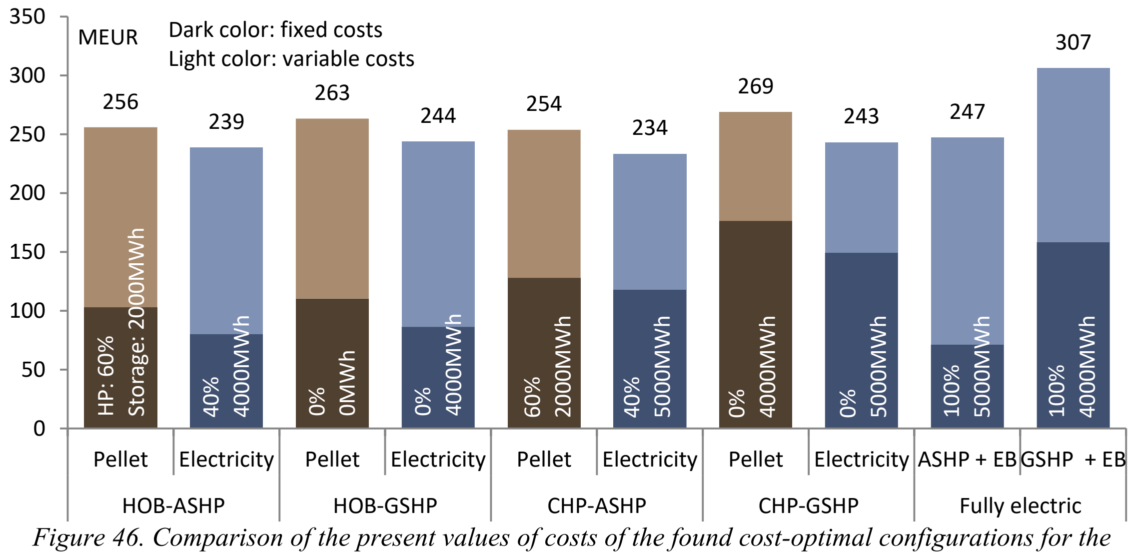

Figure 46. Comparison of the present values of costs of the found cost-optimal configurations for the different main scenarios studied and the fully electric configurations.

In Figure 47 the same results are also presented as Levelized Cost of Heat (LCOH). The value is obtained by calculating the annuity of the investment with the same WACC and calculation period as used in the PV of costs calculation, adding this cost to the yearly fixed O&M costs and variable costs and dividing the sum with the heat produced during the year. LCOH enables us to set the cost differences better into perspective. However, the value cannot be straight compared to the competing heating alternatives, such as distributed heat pumps, as the costs do not include e.g. the network-related costs comprising mostly of the annuity of the investment, maintenance-related costs, and pumping cost. Having this mentioned, the comparison between the modeled scenarios can still be made.

Taking a closer look at the electric boiler-based alternatives, it can be seen that the HOB or CHP alone as base load technology leads to almost the same LCOH with only a difference of 0.1EUR/MWh. When the optimal amount of ASHP and heat storage are included, the difference becomes 0.8EUR/MWh. Full electrification with ASHP only leads to an increase of 2.2EUR/MWh compared to the cost-optimal configuration with ASHP and CHP, and only to an increase of 0.5-0.6EUR/MWh compared to the combustion-based alternatives. If ASHP is after all seen as a technically infeasible alternative, the other possibility to fully electrify the heat production would we the GSHP alternative. However, this would add the production costs by approximately 10-12EUR/MWh compared to the most profitable and the pure combustion-based base load alternatives. In terms of maintaining the competitiveness of DH compared to other forms of heating, this may be considered a too high increase in the costs.

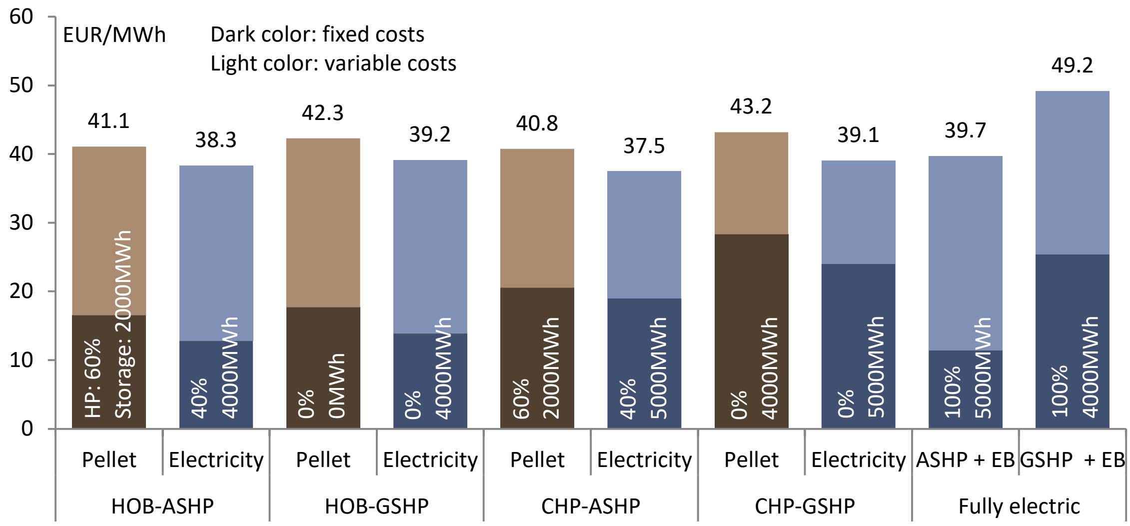

Figure 47. Comparison of the levelized cost of heat of the found cost-optimal configurations for the different main scenarios studied and the fully electric configurations.

5.7 Sensitivity Analysis

One of the largest uncertainties in the modeling is the biomass price in the future. Furthermore, the price also differs significantly according to the locations of the plants as the supply and demand balance varies considerably within the country. Therefore, as discussed in 3.1, also additional low and high scenarios for biomass prices have been considered in a sensitivity analysis. In the additional price scenarios, the price differs for both the forest chips price as well as the wood pellets price. The different price levels considered are presented in Figure 48.

It is worth to notice, that these prices address the uncertainty in biomass price only, followed by the uncertainty in the future supply and demand. Thus, they are not bound to any other uncertainties, such as economic activity or electricity prices. However, a change in biomass price in Finland would not significantly affect the Finnish electricity price as the share of biomass-based production remains fairly low. As discussed in 3.2.2, the long term price level is after all set by the opportunity costs of hydro, being mostly coal and gas-based production in central Europe.

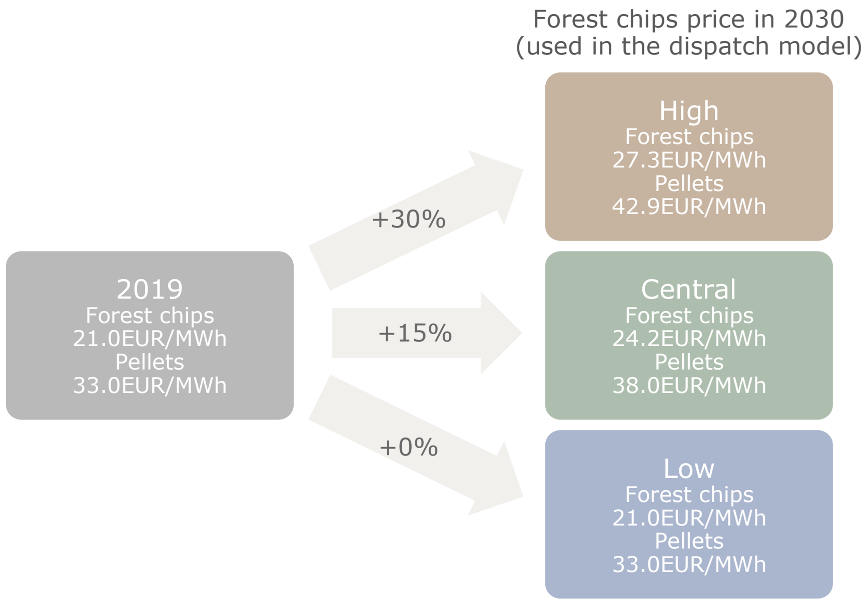

Figure 48. The different price levels for biomass in 2030 used in the sensitivity analysis.

The results of the model runs in the sensitivity analysis with the different biomass price levels are presented in Figure 49. The figure shows all the configuration scenarios with both pellets and electricity boilers as peak load production capacity and the optimal running points in each of these scenarios in low, central, and high biomass price scenarios.

When low biomass price is considered, it can be noted that the optimal amount of heat pumps decreases from the central biomass price optimum in all of the sub-scenarios where some heat pumps were included in the optimal running point. The optimal amount of air-source heat pumps would be in most cases 20% of the total base load production, but 40% if CHP and pellets as peak load capacity are considered. The decrease in the optimal amount of heat pumps would be roughly a 20% share of total base load production capacity.

No heat pumps are included in the optimal running points for the scenarios where geo-source heat pumps where considered. The decrease in the optimal heat pump capacities can be considered intuitional as the opportunity cost for heat pumps decreases. The optimal amount of heat storage capacity remained the same in almost all of the scenarios, the first scenario with pellets as peak load production being the exception as the optimal storage size decreases by 1000MWh. One reason behind this could be that the lower share of heat pumps requires less storage as no price arbitrage can be done with HOB plants.

The high biomass price level increases the optimal amount of heat pumps in all of the scenarios where air-source heat pumps where considered by 40% compared to the central biomass price level optimum. Thus, the air-source heat pumps would achieve a full or almost full dominance of the system base load production. The optimal amount of storage would decrease if pellets are used as peak load production and increase in the case of electric boilers.

The increase of the optimal storage capacity when electric boilers are used can be seen as intuitional as the increase in the electricity price dependent heat pumps usually increases the need for storage. On the other hand, the decrease of the optimal heat storage capacity when pellets are considered is less so. The reason behind this is most likely due to the variance of the usable capacity of the air-source heat pumps during the year. This is due to the dimensioning of the heat pump for the peak load situation and the change of COP during the year. Further explanations are included in the description of Figure 44. The lower capacity of heat pumps before the peak load hours leads to a situation where the base load capacity cannot be used for peak shaving as not enough of extra capacity is available before the peaks. Instead, the storage is mostly used for price arbitrage for heat pumps, and smaller storage is sufficient in this kind of operation.

When the geo-source heat pumps are considered in the system with the higher biomass price, no heat pumps would still be included in the optimal running point. This indicates, that the biomass price would have to increase very significantly before the geo-source heat pumps would become competitive compared to combustion-based production.

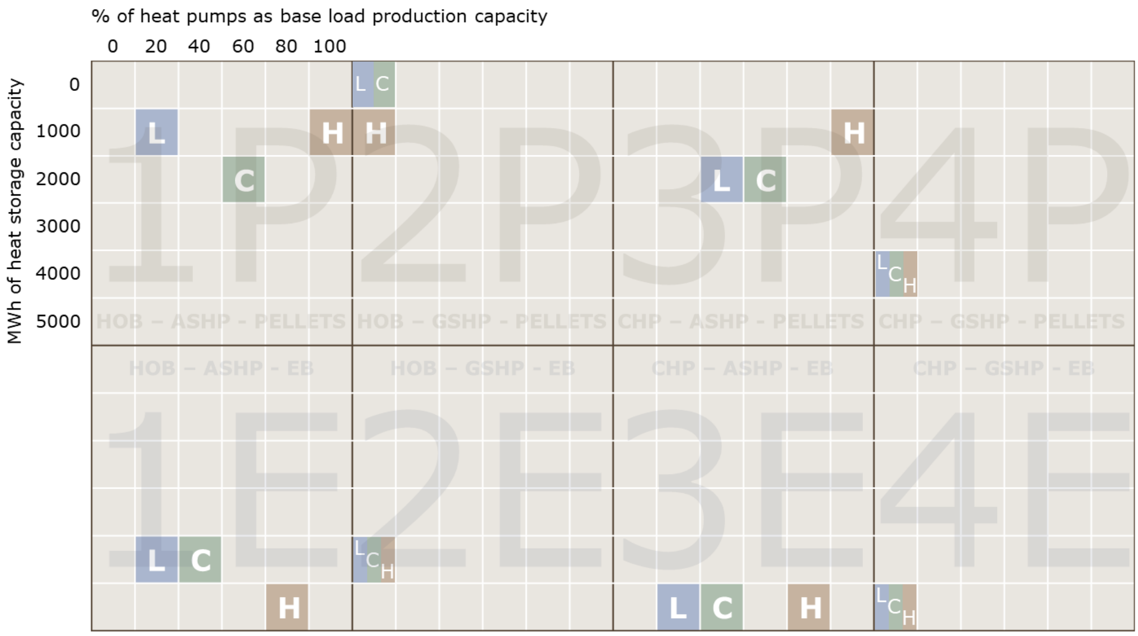

Figure 49. Sensitivity analysis for the different scenarios with the different biomass price levels (low, central, and high).

Figure 50 represents the comparison of the PV and LCOH of the cost-optimal configurations of the main scenarios as well as the ones of the fully electricity-based alternatives in the low biomass price scenario. Firstly, the pellet alternatives become more competitive, but electric boilers still remain more cost-efficient. Though the share of air-source heat pumps has decreased in the optimal configurations, the third scenario with CHP and electric boilers remains the most profitable scenario. Actually, the gap compared to the best HOB scenario increased from the 5MEUR with central biomass price to 10MEUR with the low biomass price scenario. This can be seen intuitional, as the CHP plants consume more fuel than HOB plants and do thus benefit more of the lower wood chips prices. Also in the comparison between the two fully combustion-based alternatives, CHP becomes clearly the more compelling one.

When the fully electricity-based alternatives are considered, the difference in the costs compared to the least cost alternative would become as high as 31MEUR or 5.0EUR/MWh if air-source heat pumps are considered. The difference compared to fully combustion-based base load production would also increase to 20-27MEUR or 3.2-4.3EUR/MWh. The geo-source heat pumps based alternative would be roughly 80-90MEUR or 13-14EUR/MWh more expensive than the most profitable or combustion based alternatives, and would thus be a very uncompetitive alternative.

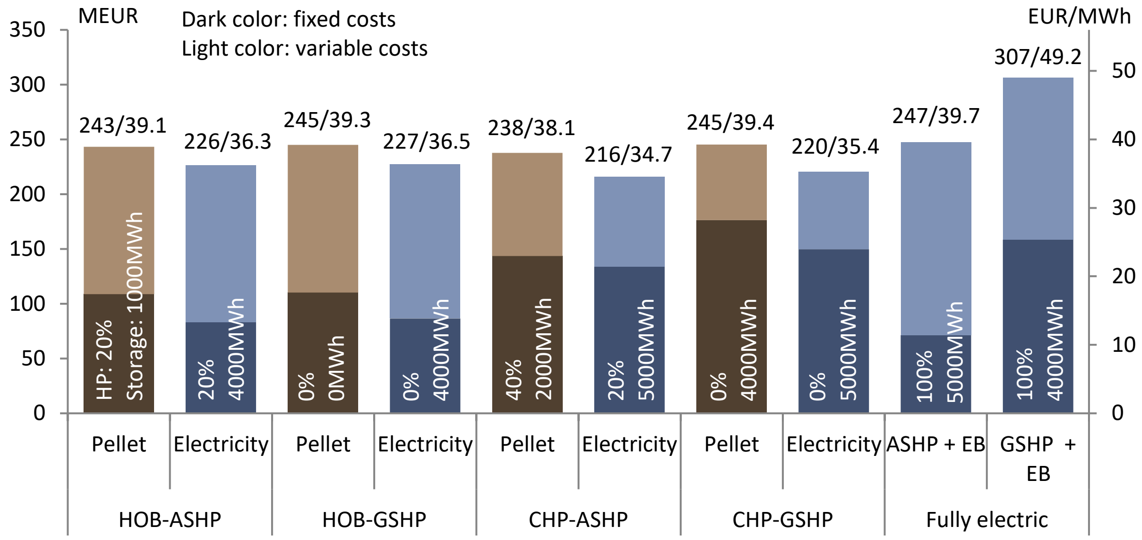

Figure 50. Comparison of the present values of costs and the levelized cost of heat of the found cost-optimal configurations for the different main scenarios studied and the fully electric configurations with low biomass price.

The same comparison with high biomass prices is presented in Figure 51. With the higher biomass prices, the dominance of the electric boilers compared to the pellet boilers becomes more apparent. The most profitable alternative is still the third scenario with electric boilers as peak load production. However, also this scenario would include as much as 80% of heat pumps of base load production. The first scenario with HOB as the remaining combustion technology would become almost as cost-efficient. The CHP only scenarios would become less profitable than the HOB scenarios.

A fully electricity-based alternative would lead to only 3MEUR or 0.6EUR/MWh higher costs than the cost-optimal alternative. Furthermore, it would be clearly cheaper than the fully combustion-based ones. The geo-source heat pumps based alternative would still be roughly 40-60MEUR or 7-10EUR/MWh more expensive than the most profitable or combustion based alternatives, and would thus still be a fairly uncompetitive alternative.

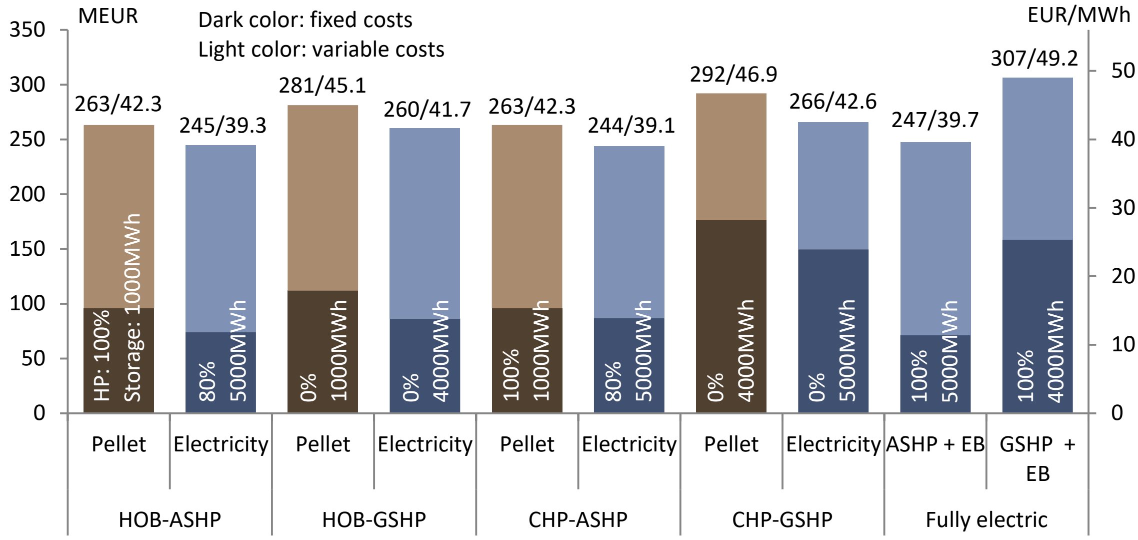

Figure 51. Comparison of the present values of costs and the levelized cost of heat of the found cost-optimal configurations for the different main scenarios studied and the fully electric configurations with high biomass price.

6 Summary and Conclusions

6.1 Discussion

The investment costs of geo-source heat pumps are high compared to other production technologies. Thus, no geo-source heat pumps would be included in a cost-optimal system. However, if the drilling costs and the uncertainties considering the costs related to drilling are to be lower in the future, geothermal heat would provide a much more stable heat source than air for the DH systems. Once the well is completed, the technology would also provide heat with much less technological uncertainties than the air-source ones.

The air-source heat pumps, on the other hand, showed clear profitability according to the modeling results. However, it has to be mentioned that these kinds of large air-to-water heat pumps have not been deployed widely in Finland, and several uncertainties are included for the technology. For example, the icing of the evaporator of the heat pumps when mild and humid air enters the evaporator and temperature decreases below zero would most likely decrease the COP somewhat from the level used in this thesis. As the temperature of the air drops approximately 6 degrees Celsius in the evaporator, the COP value would mainly decrease between the temperatures of 0-6 Celsius. The exact influence on the COP is though uncertain, and was thus not included in the study. Also, the fan electricity consumption may lower the COP of the air-source heat pumps slightly from the level used in this thesis.

According to the results of this study, it seems to be that the heat pumps have clearly more synergies with the CHP than with the HOB units. Similar kinds of results were also obtained by Valor Partners (2016), which stated that in the middle-sized DH systems heat pumps would have the role of optimizing the production of the existing CHP units and thus increasing the system profitability.

However, it has to be taken into account that the CHP units are too optimally driven in the model, and thus leads to slightly too optimal results. The phenomenon was studied by Nielsen et al. (2016). In terms of the ramping constraints this would most likely be possible, but the real-world control strategies together with the uncertainties in the heat demand and electricity price level that the producers lead to a real-world deviation from this optimum. The difference between the optimal results from the model and the achievable level in the real world can be minimized by optimized control strategies. The same observation also applies to the power-to-heat technologies, as well as the profitability of the heat storage.

A clear difference in the study in this thesis compared to many other studies, including the study by Valor Partners (2016) is that the investment costs of all the studied technologies are included. Therefore there is an assumption that no existing production capacity would be left to the network. Of course, this would most likely not be the real situation in any network that is reinvesting in production. However, as the goal of this thesis is to provide results that are universally applicable at least at some point on any network, it would be unfair for the power-to-heat technologies in the comparison if some technology would not include the investment costs.

Following this difference, the optimal level of heat pumps according to Valor Partners (2016) would have been only 5-30% of the yearly heat demand, whereas the optimal amount of ASHP this thesis was around 40-60% of the yearly heat demand. A result closer to the one obtained in this study was found by Hast et. al. 2017 which stated that the optimal capacity of heat pumps in a middle-sized network would have been 20% of the yearly peak load. In this study, the corresponding amount of ASHP would have been 20-30% of the system's peak load.

The investment costs of electric boilers are lower, and thus they seem to be a better fit for peak load production than pellet boilers. However, if the investment costs are not considered, the pellet peak option would provide at least as a cost-efficient solution. The difference depends on the level on which the electric boiler can optimize its production according to the electricity prices close to the peak load hours. If electric boilers are used, heat storage becomes imperative. It has to be mentioned, however, that the power-based component of the electric boilers is calculated inside the energy-based component as presented in 3.2.2, the distribution costs of the electric boilers are most likely slightly underestimated due to their low full load hours.

When assessing the fully electricity-based configurations as illustrated in this thesis, it has to be taken into account that the electric boilers are required to be used during the peak load hours when the electricity price is usually at its highest. This is the case due to the fact that the base load technologies, as well as the storage assessed in this thesis, do not reach the required high supply temperatures during these periods. If temperatures would not be a problem, the electric boiler could instead charge the storage slightly outside these peak load hours by optimizing according to the electricity prices, and the storage could be discharged during the peak load hours. This would require either higher supply temperatures for all of the units or lower temperature requirements of the network.

Some of the scenarios with high shares of power-to-heat technologies or CHP have their optimum storage capacity at the maximum level of this study, 1% of the yearly DH demand. However, the cost-optimality does not increase very steeply after this point. Having this mentioned, it is most likely profitable to include significantly larger heat storage than this in many system configurations if only additional storage capacity would be available at a low price. This is due to the fact that the optimal storage sizes in this thesis include the investment costs in the storage. Additional storage with low incremental investment costs could be the case if for example a cave is converted into heat storage. The optimal capacities for heat storages were found at the same magnitude as (Hast, et al., 2017). However, the results of this study show that the optimal amount of storage varies significantly according to the chosen production configuration.

6.2 Conclusions

The cost-optimal configuration for a DH network replacing all of its production with new investments would include air-source heat pumps as 40% of its base load production the rest being wood chips CHP production. As peak load capacity, electric boilers would be the preferable alternative compared to wood pellets due to their lower investment costs. Optimal storage size would be 1% or more compared to the yearly DH demand.

With the current level of investment costs, the geo-source heat pumps do not provide a competitive alternative compared to the other production technologies. If the investment costs were to drop, the geo-source heat pumps could provide a more stable load of heat with a higher average COP than the air-source heat pumps. Furthermore, the geothermal heat would provide a more reliable heat source alternative due to the uncertainties regarding air as a heat source, such as icing. Nevertheless, the good results for the air-source heat pumps shown indicate that also air should be considered as one possible heat source for heat pumps.

HOB plants would lead to more cost-optimal results than CHP plants when comparing systems where the base load capacity would fully be based on combustion technologies. However, as the CHP plants benefit more of the heat pumps and heat storages, the CHP option becomes the more optimal combustion technology to complete the base load production when power-to-heat technologies are included.

Adding air-source heat pumps to the CHP concepts significantly reduces the costs compared to CHP only. When considering HOB as the alternative base load production technology, the cost-optimality remains more stable with different air-source heat pump levels. Adding a small amount of geo-source heat pumps to a system with CHP as the alternative base load production does not increase the costs as steeply as it does when added to a system with HOB base load production.

At least a small amount of heat storage is extremely necessary if electric boilers are chosen as peak load production capacity. Usually, 1% or larger storages compared to the yearly total heat demand are found to be the optimal amount of storage. Larger heat pump shares increase the optimal storage sizes.

Full electrification of the system would cost only 2.2EUR/MWh more (or 13MEUR in present value for a medium-sized network) than the cost-optimal configuration if air-source heat pumps are chosen together with peak load electric boilers. Full electrification with geo-source heat pumps on the other would increase the costs by 11.7EUR/MWh or by 73MEUR in present value.

The sensitivity analysis showed that a lower biomass price would lead to a lower optimal amount of air-source heat pumps in the cost-optimal configuration, the optimal share being 20% of the system base load production capacity. The CHP plants would increase their attractiveness compared to HOB plants both when comparing the scenarios with or without the optimally sized heat pump capacity supplementing the system. The attractiveness of a fully electricity-based alternative with air-source heat pumps would drop compared to the central biomass price scenario, the difference compared to the cost-optimal configuration increasing from 2.2EUR/MWh with central biomass price to 5.0EUR/MWh.

With a higher biomass price, the optimal share of air-source heat pumps in the optimal configuration would increase to a very high level of 80% of total system base load production. No geo-source heat pumps would still be included in the optimal running points of the geothermal based scenarios. Thus, the biomass price would have to increase significantly before the geo-source heat pumps would become competitive compared to combustion-based production with the currently assumed investment costs for geothermal wells. Though the CHP only scenarios would become less profitable than the HOB scenarios, the optimal scenario would still include CHP as the remaining 20% of the system base load capacity. A fully electricity-based alternative would lead to only 0.6EUR/MWh higher costs than the cost-optimal alternative. The fully geo-source heat pump based alternative would still be roughly 10EUR/MWh more expensive than the most profitable production alternative.

6.3 Limitations

As the problem studied was extremely multidimensional and complicated, several assumptions had to be made to decrease the workload of the study. For example, the specific investment costs of the units compared are not linear, though the assumption was made in this thesis. The economies-of-scale is apparent especially for the CHP plants due to the high investment costs related to the turbine. Taking this into account would have some impacts on the results.

The study did neither assess the electricity network-related technical feasibilities. Especially with large amounts of electricity consuming heat production technologies, the capacity of the distribution network may become insufficient in providing power to the units during peak demand hours. Therefore, particular importance should be given for the planning of the locations of the power to heat technologies within the networks. According to Valor Partners (2016) and Dahl et al. (2019), this would be one of the most crucial aspects when assessing power-to-heat technologies.

The study also only focused on heat pump technologies as alternative technology for conventional combustion technologies. Furthermore, only two possible heat sources for the heat pumps were assessed. This was due to the simplification of the analysis, but also because that geothermal heat and air were seen as the only heat sources that would potentially provide an unlimited amount of heat and would be achievable anywhere in Finland. In reality, there would be other heat sources that would provide more easily utilizable heat and should, therefore, be exploited before building any heat pumps based on geothermal heat or air.

6.4 Future Research

Future research could include e.g. a broader study about the potential heat sources for the heat pumps and a deeper study of the geothermal heat as a heat source. The technology is promising but is still too expensive and includes risks related to the magnitude of investment costs due to several uncertainties. Also, the technical feasibility of air-to-water heat pumps serving the DH network should be studied more carefully, including the aforementioned aspects as well as the noise emissions and the noise-related restrictions in applying industrial-scale air-source heat pumps in the Finnish municipalities in a wider scale. If a DH network is chosen for a more thorough study for the electrification of heating, the grid capability to provide sufficient power for a large number of industrial-scale heat pumps and electric boilers, and the preferred locations for the units should be profoundly assessed.

The main goal of this thesis is not to introduce heat pumps to the DH systems, but to find one alternative for the combustion technologies. Thus, future research could also include a feasibility comparison between heat pumps and e.g. the modular nuclear reactors, if the nuclear reactors reach technical maturity and political acceptance in the future.

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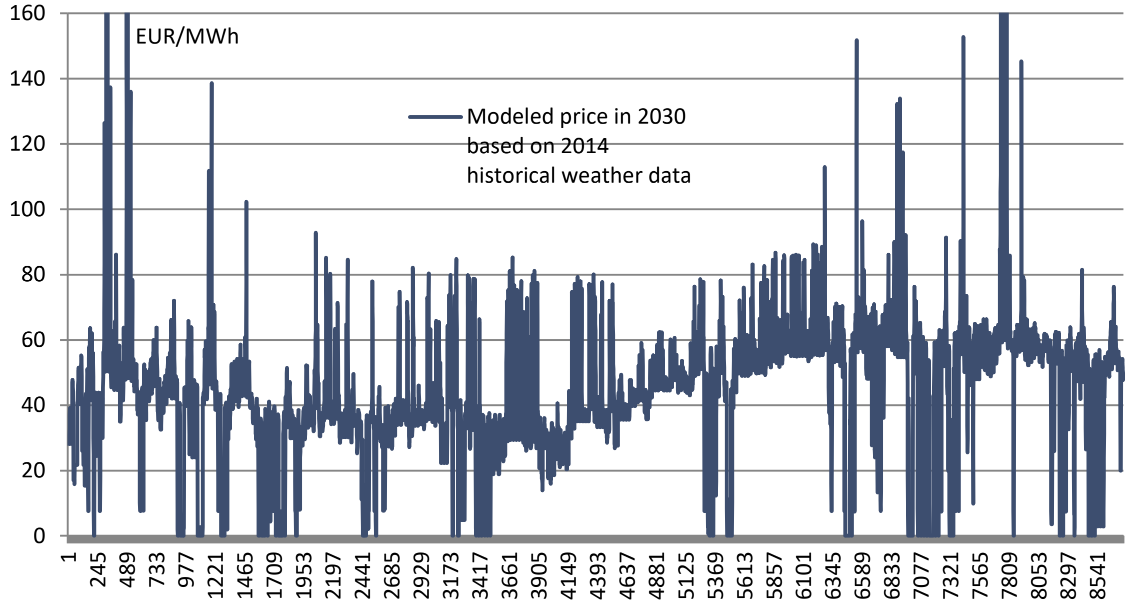
List of Appendices

Appendix 1. The hourly electricity price profile used in the modeling. The profile is a sub result from a wider electricity price analysis conducted by (Närhi, 2020).



Appendix 2. The present values of the studied scenarios in all of the running points.

PV of costs (MEUR) for the scenario HOB-ASHP-PELLET

HP share of base of total base load capacity

Storage size (MWh)	0 %	20 %	40 %	60 %	80 %	100 %
0	263.5	260.2	258.1	258.0	259.5	262.6
1000	263.7	259.2	256.7	256.1	256.8	258.7
2000	263.8	259.3	256.7	256.1	256.9	258.8
3000	264.2	259.8	257.1	256.4	257.3	259.1
4000	264.7	260.3	257.6	257.0	257.8	259.5
5000	265.1	260.8	258.2	257.5	258.3	260.0

PV of costs (MEUR) for the scenario HOB-ASHP-EB

HP share of base of total base load capacity

Storage size (MWh)	0 %	20 %	40 %	60 %	80 %	100 %
0	253.1	252.5	253.9	258.3	265.6	275.4
1000	246.2	242.8	241.6	242.7	247.1	254.1
2000	245.0	241.5	239.9	240.6	244.1	250.5
3000	244.2	240.9	239.3	239.5	242.8	249.0
4000	244.0	240.6	238.9	239.1	241.9	248.0
5000	244.0	240.7	239.0	239.1	241.6	247.5

PV of costs (MEUR) for the scenario HOB-GSHP-PELLET							
		HP share of base of total base load capacity					
		0 %	**20 %**	**40 %**	**60 %**	**80 %**	**100 %**
Storage size (MWh)	**0**	263.5	274.5	286.3	299.5	314.4	331.3
	1000	263.7	273.9	285.1	297.1	310.2	324.2
	2000	263.8	274.0	285.1	297.0	309.9	323.6
	3000	264.2	274.5	285.5	297.4	310.2	323.8
	4000	264.7	275.0	286.0	297.8	310.6	324.2
	5000	265.1	275.5	286.5	298.4	311.1	324.8

PV of costs (MEUR) for the scenario HOB-GSHP-EB							
		HP share of base of total base load capacity					
		0 %	**20 %**	**40 %**	**60 %**	**80 %**	**100 %**
Storage size (MWh)	**0**	253.1	264.6	277.1	290.8	306.2	323.3
	1000	246.2	256.6	267.9	280.2	293.6	308.8
	2000	245.0	255.4	266.7	278.7	291.9	306.9
	3000	244.2	254.7	265.9	277.9	291.2	306.6
	4000	244.0	254.5	265.7	277.7	291.1	306.6
	5000	244.0	254.6	265.8	277.9	291.3	306.9

PV of costs (MEUR) for the scenario CHP-ASHP-PELLET

Storage size (MWh)	HP share of base of total base load capacity					
	0 %	**20 %**	**40 %**	**60 %**	**80 %**	**100 %**
0	275.3	265.5	260.2	257.7	258.7	262.6
1000	270.2	261.2	256.4	254.2	255.4	258.7
2000	269.7	260.9	255.9	254.0	255.4	258.8
3000	269.4	261.0	256.0	254.2	255.7	259.1
4000	269.2	261.1	256.4	254.6	256.2	259.5
5000	269.3	261.5	256.8	255.1	256.7	260.0

PV of costs (MEUR) for the scenario CHP-ASHP-EB

Storage size (MWh)	HP share of base of total base load capacity					
	0 %	**20 %**	**40 %**	**60 %**	**80 %**	**100 %**
0	256.3	249.2	247.4	249.8	258.3	275.4
1000	246.8	239.4	236.4	236.7	241.7	254.1
2000	245.4	238.0	234.7	234.9	239.5	250.5
3000	244.4	237.4	234.0	234.0	238.5	249.0
4000	243.7	236.9	233.7	233.8	238.0	248.0
5000	243.4	236.8	233.6	233.8	238.0	247.5

PV of costs (MEUR) for the scenario CHP-GSHP-PELLET

Storage size (MWh)	HP share of base of total base load capacity					
	0 %	**20 %**	**40 %**	**60 %**	**80 %**	**100 %**
0	275.3	280.2	288.9	300.1	314.3	331.3
1000	270.2	276.5	285.7	296.6	309.7	324.2
2000	269.7	276.3	285.5	296.4	309.3	323.6
3000	269.4	276.3	285.5	296.4	309.5	323.8
4000	269.2	276.5	285.7	296.8	309.9	324.2
5000	269.3	276.7	286.0	297.2	310.4	324.8

PV of costs (MEUR) for the scenario CHP-GSHP-EB

Storage size (MWh)	HP share of base of total base load capacity					
	0 %	**20 %**	**40 %**	**60 %**	**80 %**	**100 %**
0	256.3	262.8	273.4	286.7	303.4	323.3
1000	246.8	254.2	264.5	276.8	291.4	308.8
2000	245.4	252.9	263.2	275.2	289.7	306.9
3000	244.4	252.3	262.5	274.6	288.9	306.6
4000	243.7	251.8	262.1	274.3	288.7	306.6
5000	243.4	251.6	262.0	274.3	288.9	306.9

Appendix 3. The present values and LCOH of all the calculated configurations and running points in the different biomass price scenarios.

Scenario	Running point	Storage MWh	HP share of base load	PV Low MEUR	PV Central MEUR	PV High MEUR	LCOH Low EUR/MWh	LCOH Central EUR/MWh	LCOH High EUR/MWh
1P	1	0	0 %	245.2	263.5	281.3	39.3	42.3	45.1
1P	2	0	20 %	244.1	260.2	275.7	39.2	41.8	44.2
1P	3	0	40 %	244.9	258.1	270.4	39.3	41.4	43.4
1P	4	0	60 %	247.5	258.0	267.6	39.7	41.4	42.9
1P	5	0	80 %	251.8	259.5	266.7	40.4	41.6	42.8
1P	6	0	100 %	257.3	262.6	267.6	41.3	42.1	42.9
1P	7	1000	0 %	245.6	263.7	281.2	39.4	42.3	45.1
1P	8	1000	20 %	243.4	259.2	274.2	39.1	41.6	44.0
1P	9	1000	40 %	243.8	256.7	268.6	39.1	41.2	43.1
1P	10	1000	60 %	246.0	256.1	265.3	39.5	41.1	42.6
1P	11	1000	80 %	249.4	256.8	263.7	40.0	41.2	42.3
1P	12	1000	100 %	253.7	258.7	263.3	40.7	41.5	42.3
1P	13	2000	0 %	245.8	263.8	281.3	39.4	42.3	45.2
1P	14	2000	20 %	243.5	259.3	274.3	39.1	41.6	44.0
1P	15	2000	40 %	243.9	256.7	268.6	39.1	41.2	43.1
1P	16	2000	60 %	246.1	256.1	265.2	39.5	41.1	42.6
1P	17	2000	80 %	249.6	256.9	263.7	40.1	41.2	42.3
1P	18	2000	100 %	253.9	258.8	263.3	40.7	41.5	42.3
1P	19	3000	0 %	246.2	264.2	281.7	39.5	42.4	45.2
1P	20	3000	20 %	244.0	259.8	274.7	39.2	41.7	44.1
1P	21	3000	40 %	244.3	257.1	269.0	39.2	41.3	43.2
1P	22	3000	60 %	246.6	256.4	265.5	39.6	41.2	42.6
1P	23	3000	80 %	250.0	257.3	264.0	40.1	41.3	42.4
1P	24	3000	100 %	254.3	259.1	263.6	40.8	41.6	42.3
1P	25	4000	0 %	246.7	264.7	282.1	39.6	42.5	45.3
1P	26	4000	20 %	244.5	260.3	275.2	39.2	41.8	44.2
1P	27	4000	40 %	244.9	257.6	269.5	39.3	41.3	43.3
1P	28	4000	60 %	247.1	257.0	266.0	39.7	41.2	42.7
1P	29	4000	80 %	250.6	257.8	264.4	40.2	41.4	42.4
1P	30	4000	100 %	254.8	259.5	263.9	40.9	41.6	42.4
1P	31	5000	0 %	247.1	265.1	282.5	39.7	42.5	45.3
1P	32	5000	20 %	245.1	260.8	275.7	39.3	41.9	44.2
1P	33	5000	40 %	245.5	258.2	270.1	39.4	41.4	43.3
1P	34	5000	60 %	247.7	257.5	266.5	39.7	41.3	42.8
1P	35	5000	80 %	251.1	258.3	264.9	40.3	41.5	42.5
1P	36	5000	100 %	255.3	260.0	264.4	41.0	41.7	42.4
1E	1	0	0 %	236.8	253.1	268.9	38.0	40.6	43.2
1E	2	0	20 %	238.7	252.5	265.6	38.3	40.5	42.6
1E	3	0	40 %	243.5	253.9	263.4	39.1	40.7	42.3
1E	4	0	60 %	251.4	258.3	264.6	40.3	41.5	42.5

1E	5	0	80 %	262.2	265.6	268.7	42.1	42.6	43.1
1E	6	0	100 %	275.4	275.4	275.4	44.2	44.2	44.2
1E	7	1000	0 %	229.6	246.2	262.2	36.9	39.5	42.1
1E	8	1000	20 %	228.7	242.8	256.0	36.7	39.0	41.1
1E	9	1000	40 %	230.9	241.6	251.5	37.1	38.8	40.4
1E	10	1000	60 %	235.5	242.7	249.2	37.8	38.9	40.0
1E	11	1000	80 %	243.5	247.1	250.3	39.1	39.7	40.2
1E	12	1000	100 %	254.1	254.1	254.1	40.8	40.8	40.8
1E	13	2000	0 %	228.4	245.0	261.1	36.7	39.3	41.9
1E	14	2000	20 %	227.4	241.5	254.9	36.5	38.8	40.9
1E	15	2000	40 %	229.2	239.9	250.0	36.8	38.5	40.1
1E	16	2000	60 %	233.4	240.6	247.1	37.5	38.6	39.7
1E	17	2000	80 %	240.5	244.1	247.4	38.6	39.2	39.7
1E	18	2000	100 %	250.5	250.5	250.5	40.2	40.2	40.2
1E	19	3000	0 %	227.5	244.2	260.4	36.5	39.2	41.8
1E	20	3000	20 %	226.7	240.9	254.3	36.4	38.7	40.8
1E	21	3000	40 %	228.5	239.3	249.4	36.7	38.4	40.0
1E	22	3000	60 %	232.3	239.5	246.1	37.3	38.4	39.5
1E	23	3000	80 %	239.2	242.8	246.0	38.4	39.0	39.5
1E	24	3000	100 %	249.0	249.0	249.0	40.0	40.0	40.0
1E	25	4000	0 %	227.3	244.0	260.1	36.5	39.2	41.7
1E	26	4000	20 %	226.3	240.6	254.0	36.3	38.6	40.8
1E	27	4000	40 %	228.1	238.9	249.0	36.6	38.3	40.0
1E	28	4000	60 %	231.9	239.1	245.7	37.2	38.4	39.4
1E	29	4000	80 %	238.4	241.9	245.2	38.3	38.8	39.4
1E	30	4000	100 %	248.0	248.0	248.0	39.8	39.8	39.8
1E	31	5000	0 %	227.3	244.0	260.3	36.5	39.2	41.8
1E	32	5000	20 %	226.4	240.7	254.2	36.3	38.6	40.8
1E	33	5000	40 %	228.1	239.0	249.1	36.6	38.4	40.0
1E	34	5000	60 %	231.8	239.1	245.7	37.2	38.4	39.4
1E	35	5000	80 %	238.0	241.6	244.9	38.2	38.8	39.3
1E	36	5000	100 %	247.5	247.5	247.5	39.7	39.7	39.7
2P	1	0	0 %	245.2	263.5	281.3	39.3	42.3	45.1
2P	2	0	20 %	258.9	274.5	289.1	41.6	44.0	46.4
2P	3	0	40 %	274.2	286.3	297.4	44.0	46.0	47.7
2P	4	0	60 %	290.8	299.5	307.4	46.7	48.1	49.3
2P	5	0	80 %	309.0	314.4	319.2	49.6	50.5	51.2
2P	6	0	100 %	328.9	331.3	333.5	52.8	53.2	53.5
2P	7	1000	0 %	245.6	263.7	281.2	39.4	42.3	45.1
2P	8	1000	20 %	258.6	273.9	288.3	41.5	44.0	46.3
2P	9	1000	40 %	273.1	285.1	295.9	43.8	45.8	47.5
2P	10	1000	60 %	288.6	297.1	304.7	46.3	47.7	48.9
2P	11	1000	80 %	305.1	310.2	314.7	49.0	49.8	50.5
2P	12	1000	100 %	322.3	324.2	326.0	51.7	52.0	52.3

2P	13	2000	0 %	245.8	263.8	281.3	39.4	42.3	45.2
2P	14	2000	20 %	258.8	274.0	288.4	41.5	44.0	46.3
2P	15	2000	40 %	273.2	285.1	295.9	43.8	45.8	47.5
2P	16	2000	60 %	288.6	297.0	304.5	46.3	47.7	48.9
2P	17	2000	80 %	304.9	309.9	314.3	48.9	49.7	50.4
2P	18	2000	100 %	321.9	323.6	325.2	51.7	51.9	52.2
2P	19	3000	0 %	246.2	264.2	281.7	39.5	42.4	45.2
2P	20	3000	20 %	259.3	274.5	288.8	41.6	44.0	46.3
2P	21	3000	40 %	273.7	285.5	296.3	43.9	45.8	47.6
2P	22	3000	60 %	289.0	297.4	304.8	46.4	47.7	48.9
2P	23	3000	80 %	305.3	310.2	314.5	49.0	49.8	50.5
2P	24	3000	100 %	322.1	323.8	325.4	51.7	52.0	52.2
2P	25	4000	0 %	246.7	264.7	282.1	39.6	42.5	45.3
2P	26	4000	20 %	259.8	275.0	289.2	41.7	44.1	46.4
2P	27	4000	40 %	274.2	286.0	296.7	44.0	45.9	47.6
2P	28	4000	60 %	289.5	297.8	305.2	46.5	47.8	49.0
2P	29	4000	80 %	305.8	310.6	314.8	49.1	49.8	50.5
2P	30	4000	100 %	322.6	324.2	325.7	51.8	52.0	52.3
2P	31	5000	0 %	247.1	265.1	282.5	39.7	42.5	45.3
2P	32	5000	20 %	260.3	275.5	289.7	41.8	44.2	46.5
2P	33	5000	40 %	274.7	286.5	297.2	44.1	46.0	47.7
2P	34	5000	60 %	290.1	298.4	305.7	46.6	47.9	49.1
2P	35	5000	80 %	306.3	311.1	315.3	49.2	49.9	50.6
2P	36	5000	100 %	323.2	324.8	326.3	51.9	52.1	52.4
2E	1	0	0 %	236.8	253.1	268.9	38.0	40.6	43.2
2E	2	0	20 %	251.2	264.6	277.3	40.3	42.5	44.5
2E	3	0	40 %	267.1	277.1	286.0	42.9	44.5	45.9
2E	4	0	60 %	284.3	290.8	296.5	45.6	46.7	47.6
2E	5	0	80 %	303.1	306.2	308.7	48.6	49.1	49.5
2E	6	0	100 %	323.3	323.3	323.3	51.9	51.9	51.9
2E	7	1000	0 %	229.6	246.2	262.2	36.9	39.5	42.1
2E	8	1000	20 %	242.9	256.6	269.4	39.0	41.2	43.2
2E	9	1000	40 %	257.7	267.9	277.2	41.4	43.0	44.5
2E	10	1000	60 %	273.4	280.2	286.1	43.9	45.0	45.9
2E	11	1000	80 %	290.3	293.6	296.3	46.6	47.1	47.6
2E	12	1000	100 %	308.8	308.8	308.8	49.6	49.6	49.6
2E	13	2000	0 %	228.4	245.0	261.1	36.7	39.3	41.9
2E	14	2000	20 %	241.6	255.4	268.3	38.8	41.0	43.1
2E	15	2000	40 %	256.3	266.7	276.0	41.1	42.8	44.3
2E	16	2000	60 %	271.9	278.7	284.7	43.6	44.7	45.7
2E	17	2000	80 %	288.6	291.9	294.7	46.3	46.9	47.3
2E	18	2000	100 %	306.9	306.9	306.9	49.3	49.3	49.3
2E	19	3000	0 %	227.5	244.2	260.4	36.5	39.2	41.8
2E	20	3000	20 %	240.8	254.7	267.6	38.7	40.9	42.9

2E	21	3000	40 %	255.5	265.9	275.3	41.0	42.7	44.2
2E	22	3000	60 %	271.1	277.9	283.9	43.5	44.6	45.6
2E	23	3000	80 %	287.8	291.2	294.0	46.2	46.7	47.2
2E	24	3000	100 %	306.6	306.6	306.6	49.2	49.2	49.2
2E	25	4000	0 %	227.3	244.0	260.1	36.5	39.2	41.7
2E	26	4000	20 %	240.6	254.5	267.4	38.6	40.8	42.9
2E	27	4000	40 %	255.2	265.7	275.1	41.0	42.6	44.1
2E	28	4000	60 %	270.9	277.7	283.7	43.5	44.6	45.5
2E	29	4000	80 %	287.7	291.1	293.9	46.2	46.7	47.2
2E	30	4000	100 %	306.6	306.6	306.6	49.2	49.2	49.2
2E	31	5000	0 %	227.3	244.0	260.3	36.5	39.2	41.8
2E	32	5000	20 %	240.7	254.6	267.5	38.6	40.9	42.9
2E	33	5000	40 %	255.4	265.8	275.2	41.0	42.7	44.2
2E	34	5000	60 %	271.0	277.9	283.9	43.5	44.6	45.6
2E	35	5000	80 %	287.9	291.3	294.0	46.2	46.7	47.2
2E	36	5000	100 %	306.9	306.9	306.9	49.2	49.2	49.2
3P	1	0	0 %	251.7	275.3	298.0	40.4	44.2	47.8
3P	2	0	20 %	244.0	265.5	285.5	39.2	42.6	45.8
3P	3	0	40 %	242.1	260.2	276.9	38.9	41.8	44.4
3P	4	0	60 %	243.5	257.7	270.7	39.1	41.4	43.4
3P	5	0	80 %	248.8	258.7	267.6	39.9	41.5	42.9
3P	6	0	100 %	257.3	262.6	267.6	41.3	42.1	42.9
3P	7	1000	0 %	246.2	270.2	293.1	39.5	43.4	47.0
3P	8	1000	20 %	239.4	261.2	281.7	38.4	41.9	45.2
3P	9	1000	40 %	238.1	256.4	273.2	38.2	41.1	43.9
3P	10	1000	60 %	240.1	254.2	267.0	38.5	40.8	42.8
3P	11	1000	80 %	245.8	255.4	264.1	39.5	41.0	42.4
3P	12	1000	100 %	253.7	258.7	263.3	40.7	41.5	42.3
3P	13	2000	0 %	245.7	269.7	292.6	39.4	43.3	47.0
3P	14	2000	20 %	239.1	260.9	281.4	38.4	41.9	45.2
3P	15	2000	40 %	237.7	255.9	272.7	38.1	41.1	43.8
3P	16	2000	60 %	239.9	254.0	266.8	38.5	40.8	42.8
3P	17	2000	80 %	245.9	255.4	263.9	39.5	41.0	42.3
3P	18	2000	100 %	253.9	258.8	263.3	40.7	41.5	42.3
3P	19	3000	0 %	245.4	269.4	292.3	39.4	43.2	46.9
3P	20	3000	20 %	239.2	261.0	281.3	38.4	41.9	45.2
3P	21	3000	40 %	237.8	256.0	272.8	38.2	41.1	43.8
3P	22	3000	60 %	240.1	254.2	267.0	38.5	40.8	42.9
3P	23	3000	80 %	246.3	255.7	264.1	39.5	41.0	42.4
3P	24	3000	100 %	254.3	259.1	263.6	40.8	41.6	42.3
3P	25	4000	0 %	245.3	269.2	292.2	39.4	43.2	46.9
3P	26	4000	20 %	239.5	261.1	281.4	38.4	41.9	45.2
3P	27	4000	40 %	238.1	256.4	273.1	38.2	41.1	43.8
3P	28	4000	60 %	240.5	254.6	267.4	38.6	40.9	42.9

3P	29	4000	80 %	246.8	256.2	264.6	39.6	41.1	42.5
3P	30	4000	100 %	254.8	259.5	263.9	40.9	41.6	42.4
3P	31	5000	0 %	245.4	269.3	292.2	39.4	43.2	46.9
3P	32	5000	20 %	239.8	261.5	281.7	38.5	42.0	45.2
3P	33	5000	40 %	238.5	256.8	273.5	38.3	41.2	43.9
3P	34	5000	60 %	241.0	255.1	267.9	38.7	40.9	43.0
3P	35	5000	80 %	247.3	256.7	265.0	39.7	41.2	42.5
3P	36	5000	100 %	255.3	260.0	264.4	41.0	41.7	42.4
3E	1	0	0 %	234.4	256.3	277.5	37.6	41.1	44.5
3E	2	0	20 %	229.8	249.2	267.6	36.9	40.0	42.9
3E	3	0	40 %	231.7	247.4	261.9	37.2	39.7	42.0
3E	4	0	60 %	238.6	249.8	260.0	38.3	40.1	41.7
3E	5	0	80 %	252.4	258.3	263.7	40.5	41.5	42.3
3E	6	0	100 %	275.4	275.4	275.4	44.2	44.2	44.2
3E	7	1000	0 %	224.2	246.8	268.7	36.0	39.6	43.1
3E	8	1000	20 %	219.1	239.4	258.6	35.2	38.4	41.5
3E	9	1000	40 %	220.0	236.4	251.7	35.3	37.9	40.4
3E	10	1000	60 %	225.0	236.7	247.4	36.1	38.0	39.7
3E	11	1000	80 %	235.5	241.7	247.3	37.8	38.8	39.7
3E	12	1000	100 %	253.8	253.8	253.8	40.7	40.7	40.7
3E	13	2000	0 %	222.6	245.4	267.3	35.7	39.4	42.9
3E	14	2000	20 %	217.6	238.0	257.3	34.9	38.2	41.3
3E	15	2000	40 %	218.2	234.7	250.1	35.0	37.7	40.1
3E	16	2000	60 %	223.1	234.9	245.8	35.8	37.7	39.4
3E	17	2000	80 %	233.3	239.5	245.2	37.4	38.4	39.3
3E	18	2000	100 %	250.0	250.0	250.0	40.1	40.1	40.1
3E	19	3000	0 %	221.5	244.4	266.5	35.6	39.2	42.8
3E	20	3000	20 %	216.9	237.4	256.7	34.8	38.1	41.2
3E	21	3000	40 %	217.4	234.0	249.5	34.9	37.6	40.0
3E	22	3000	60 %	222.1	234.0	245.0	35.6	37.6	39.3
3E	23	3000	80 %	232.3	238.5	244.2	37.3	38.3	39.2
3E	24	3000	100 %	248.5	248.5	248.5	39.9	39.9	39.9
3E	25	4000	0 %	220.8	243.7	266.0	35.4	39.1	42.7
3E	26	4000	20 %	216.4	236.9	256.3	34.7	38.0	41.1
3E	27	4000	40 %	217.0	233.7	249.2	34.8	37.5	40.0
3E	28	4000	60 %	221.8	233.8	244.8	35.6	37.5	39.3
3E	29	4000	80 %	231.8	238.0	243.7	37.2	38.2	39.1
3E	30	4000	100 %	247.4	247.4	247.4	39.7	39.7	39.7
3E	31	5000	0 %	220.4	243.4	265.7	35.4	39.1	42.6
3E	32	5000	20 %	216.2	236.8	256.2	34.7	38.0	41.1
3E	33	5000	40 %	216.9	233.6	249.2	34.8	37.5	40.0
3E	34	5000	60 %	221.8	233.8	244.8	35.6	37.5	39.3
3E	35	5000	80 %	231.7	238.0	243.6	37.2	38.2	39.1
3E	36	5000	100 %	246.8	246.8	246.8	39.6	39.6	39.6

4P	1	0	0 %	251.7	275.3	298.0	40.4	44.2	47.8
4P	2	0	20 %	259.2	280.2	299.8	41.6	45.0	48.1
4P	3	0	40 %	271.7	288.9	304.6	43.6	46.4	48.9
4P	4	0	60 %	287.2	300.1	311.7	46.1	48.2	50.0
4P	5	0	80 %	306.3	314.3	321.4	49.2	50.4	51.6
4P	6	0	100 %	328.9	331.3	333.5	52.8	53.2	53.5
4P	7	1000	0 %	246.2	270.2	293.1	39.5	43.4	47.0
4P	8	1000	20 %	255.1	276.5	296.4	40.9	44.4	47.6
4P	9	1000	40 %	268.1	285.7	301.7	43.0	45.8	48.4
4P	10	1000	60 %	283.5	296.6	308.3	45.5	47.6	49.5
4P	11	1000	80 %	301.9	309.7	316.6	48.5	49.7	50.8
4P	12	1000	100 %	322.3	324.2	326.0	51.7	52.0	52.3
4P	13	2000	0 %	245.7	269.7	292.6	39.4	43.3	47.0
4P	14	2000	20 %	254.9	276.3	296.2	40.9	44.3	47.5
4P	15	2000	40 %	267.8	285.5	301.5	43.0	45.8	48.4
4P	16	2000	60 %	283.2	296.4	308.1	45.4	47.6	49.4
4P	17	2000	80 %	301.6	309.3	316.2	48.4	49.6	50.7
4P	18	2000	100 %	321.9	323.6	325.2	51.7	51.9	52.2
4P	19	3000	0 %	245.4	269.4	292.3	39.4	43.2	46.9
4P	20	3000	20 %	254.9	276.3	296.1	40.9	44.3	47.5
4P	21	3000	40 %	267.8	285.5	301.4	43.0	45.8	48.4
4P	22	3000	60 %	283.3	296.4	308.1	45.5	47.6	49.5
4P	23	3000	80 %	301.8	309.5	316.3	48.4	49.7	50.8
4P	24	3000	100 %	322.1	323.7	325.3	51.7	52.0	52.2
4P	25	4000	0 %	245.3	269.2	292.2	39.4	43.2	46.9
4P	26	4000	20 %	255.2	276.5	296.2	41.0	44.4	47.5
4P	27	4000	40 %	268.0	285.7	301.5	43.0	45.8	48.4
4P	28	4000	60 %	283.6	296.8	308.4	45.5	47.6	49.5
4P	29	4000	80 %	302.3	309.9	316.6	48.5	49.7	50.8
4P	30	4000	100 %	322.5	324.1	325.6	51.8	52.0	52.3
4P	31	5000	0 %	245.4	269.3	292.3	39.4	43.2	46.9
4P	32	5000	20 %	255.5	276.7	296.4	41.0	44.4	47.6
4P	33	5000	40 %	268.4	286.0	301.9	43.1	45.9	48.4
4P	34	5000	60 %	284.1	297.2	308.9	45.6	47.7	49.6
4P	35	5000	80 %	302.8	310.4	317.1	48.6	49.8	50.9
4P	36	5000	100 %	323.1	324.6	326.0	51.8	52.1	52.3
4E	1	0	0 %	234.4	256.3	277.5	37.6	41.1	44.5
4E	2	0	20 %	243.6	262.8	280.9	39.1	42.2	45.1
4E	3	0	40 %	258.1	273.4	287.4	41.4	43.9	46.1
4E	4	0	60 %	275.8	286.7	296.4	44.3	46.0	47.6
4E	5	0	80 %	297.7	303.4	308.4	47.8	48.7	49.5
4E	6	0	100 %	323.3	323.3	323.3	51.9	51.9	51.9
4E	7	1000	0 %	224.2	246.8	268.7	36.0	39.6	43.1
4E	8	1000	20 %	234.2	254.2	272.9	37.6	40.8	43.8

4E	9	1000	40 %	248.4	264.5	279.2	39.9	42.4	44.8
4E	10	1000	60 %	265.3	276.8	287.0	42.6	44.4	46.1
4E	11	1000	80 %	285.4	291.4	296.7	45.8	46.8	47.6
4E	12	1000	100 %	308.1	308.1	308.1	49.5	49.5	49.5
4E	13	2000	0 %	222.6	245.4	267.3	35.7	39.4	42.9
4E	14	2000	20 %	232.8	252.9	271.7	37.4	40.6	43.6
4E	15	2000	40 %	246.8	263.2	278.0	39.6	42.2	44.6
4E	16	2000	60 %	263.5	275.2	285.7	42.3	44.2	45.8
4E	17	2000	80 %	283.5	289.7	295.1	45.5	46.5	47.4
4E	18	2000	100 %	306.1	306.1	306.1	49.1	49.1	49.1
4E	19	3000	0 %	221.5	244.4	266.5	35.6	39.2	42.8
4E	20	3000	20 %	232.0	252.3	271.1	37.2	40.5	43.5
4E	21	3000	40 %	246.1	262.5	277.4	39.5	42.1	44.5
4E	22	3000	60 %	262.8	274.6	285.1	42.2	44.1	45.8
4E	23	3000	80 %	282.7	288.9	294.4	45.4	46.4	47.2
4E	24	3000	100 %	305.3	305.3	305.3	49.0	49.0	49.0
4E	25	4000	0 %	220.8	243.7	266.0	35.4	39.1	42.7
4E	26	4000	20 %	231.6	251.8	270.7	37.2	40.4	43.4
4E	27	4000	40 %	245.6	262.1	277.0	39.4	42.1	44.5
4E	28	4000	60 %	262.4	274.3	284.9	42.1	44.0	45.7
4E	29	4000	80 %	282.5	288.7	294.2	45.3	46.3	47.2
4E	30	4000	100 %	305.2	305.2	305.2	49.0	49.0	49.0
4E	31	5000	0 %	220.4	243.4	265.7	35.4	39.1	42.6
4E	32	5000	20 %	231.3	251.6	270.6	37.1	40.4	43.4
4E	33	5000	40 %	245.4	262.0	276.9	39.4	42.0	44.4
4E	34	5000	60 %	262.4	274.3	284.9	42.1	44.0	45.7
4E	35	5000	80 %	282.6	288.9	294.3	45.4	46.4	47.2
4E	36	5000	100 %	305.4	305.4	305.4	49.0	49.0	49.0